Investigating the subjective experience of using sensory augmentation devices.

Scientific studies of Cognitive Technologies

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In this text I will present the general structure of a research programme that we have been pursuing at Compiegne (COSTECH, CRED group) over the last ten years. The so-called "Sensory Substitution Devices" implement an extreme form of coupling between the organism and the environment which is thereby highly revealing. This is the inspiration for an approach to cognitive technologies that is both philosophical and scientific, and which has the ambition of being both fundamental and systematic[1]. Before presenting some of the results of this research, and discussing their epistemological framework, I will start by recalling the best-known of these devices. This will enable me to introduce the main lines of our approach, and the methodology which we use.

I. Tactile Vision Substitution System

I.1. First results

Our programme is based on an extension of pioneering work of Bach-y-Rita on "sensory substitution" systems. These devices have been developed, since the end of the 60's, in order to help persons with congenital or acquired visual impairment. The first "Tactile Vision Substitution System" (TVSS) converted a visual image captured by a video camera into a tactile "image" composed of a 20 x 20 array of stimulators placed either on the back or on the chest (Bach y Rita 1972, Collins 1973) or now on the tongue (Bach y Rita 2005). The initial studies with this device produced important results which are quite fundamental, and whose validity and relevance has only been confirmed and amplified by subsequent research :

1) Firstly, the presentation of shapes to an immobile camera only permits a very limited discrimination of the received stimuli, and the latter are perceived as being situated on the surface of the skin. Thus, the simple substitution of an entry via the optic nerve by a tactile entry does not, in itself, give access to spatial perception. However, if the subject disposes of the capacity to actively manipulate the camera (movements from left to right, up and down, zoom), he or she develops a spectacular capacity to recognize shapes. The first step is learning how variations in sensation follow from actions : when the camera is moved from left to right, the stimuli on the skin shift from right to left; when zooming in, the stimuli expand, etc. When the

[1] This text is a summary which draws largely on various studies performed in our group, and in particular on an article written recently for the European network "Enactive Interfaces" : Lenay C., Declerck G., Gapenne O., Maillet B., Stewart J., Thouvenin I. (2008) Technical mediation of sensorimotor coupling : a minimalist approach, *ENACTIVE08 5th International Conference on Enactive Interfaces*, pp. 36-41.

subject has learned to aim the camera at a target, he or she begins to discriminate lines and surfaces, and then to recognize familiar objects of increasing complexity to the point of being able to discriminate faces.

2) Secondly, this recognition is accompanied by a "projection" of the percepts into objects with external spatial localisation. Initially, the subject feels the successive stimulations on the surface of the skin. However, as perceptual learning proceeds, these sensations of touch fade from consciousness, and are replaced by the perception of stable objects, situated "out there" in front of the subject. Thus, according to the testimony of the subjects, the proximal irritations produced by the tactile display unit are quite distinct from the perception itself. This subjective localisation of objects in space comes about quite rapidly, after 5 - 15 hours of familiarisation and learning. Congenitally blind subjects discover perceptual concepts which are radically new for them, such as parallax, shadows, the interposition of objects, etc. Certain classical optical illusions are spontaneously reproduced (Bach y Rita 1982). These experiments can be performed not only with visually impaired subjects, but also by blindfolded normal subjects.

The essential role of action in the progressive emergence of structured percepts lends support to the hypotheses of active perception. In this perspective, we abandon the conception of perception as a process in which the system passively receives an input in the form of "information", and then performs computational operations in order identify objects and events in the form of internal representations. On the contrary, it is by means of his own actions that the subject seeks and constructs the regularities in the relations between action and sensation. What is perceived and recognized is not so much invariants of sensation, but rather invariants in the circular sensori-motor loops that are inseparable from the activity of the subject[2]. It follows that richness of perception depends as much (if not more) on the qualities of action (mobility, rapidity, and indeed the whole range of actions that are qualitatively possible) than on the qualities of sensation (spectral range, the number of sensors, etc).[3]

We find the same characteristics for other perceptual supplementation devices. For example, manipulating visual-sound systems such as “The Voice” or “Vibe” also gives rise to the perception of complex forms situated in a distal space. However, none of these various aids to sensory handicap has met with the social and economic success that might have been expected.

These systems of perceptual supplementation thus clearly pose three important questions, corresponding to three major aspects of cognitive technologies. These are: (1) the spatial perception of distal objects; (2) the recognition of complex shapes; and (3) their social adoption, which appears to be problematical. For the first point (1), we have here a remarkable opportunity for following closely the genesis of the perceptual space corresponding to each technical mediation, and for studying how a tool that is grasped

[2] Gibson, J.J. (1966) *The senses considered as perceptual systems*. Boston: Houghton Mifflin.
Gibson, J.J. (1986) *The ecological approach to visual perception*. Hillsdale, Nj: Erlbaum.
Paillard (Ed.), *Brain and space* (pp.81-111). Oxford : Oxford University Press.
Varela, F. (1979). *Principles of Biological Autonomy*, New York: Elsevier.
Turvey, M. T. and Carello, C. (1995). Some Dynamical Themes in Perception and Action. In R.F. Port & T. Van Gelder (Eds.) *Mind as Motion*. Cambridge, MA: MIT Press.

[3] Lenay, C., Canu, S. & Villon P. ‘Technology and perception : the contribution of sensory substitution systems’, in *Proceedings of the Second International Conference on Cognitive Technology,* pp. 44-53. Aizu, Japan, Los Alamitos , CA. (1997).
Auvray, M. ‘Remplacer un sens par un autre : La suppléance perceptive’, in P. Fuchs, G. Moreau & J-.P. Papin (eds) *Le Traité de la réalité virtuelle III*, Vol.1, pp. 173-88. Paris : Les Presses de l’Ecole des mines. (2006).

reconfigures the possibilities for acting and feeling. For the second point (2), we shall see that perceptual supplementation systems make it possible to analyse very precisely the dynamics of shape perception; how it is that the reading of spatial inscriptions and interactions with the arrangements of the technical environment participate in cognitive activity. For the third point (3), it is necessary to understand how the constitution of aesthetic values goes together with the collective institution of social meanings that use of the tool brings about. This corresponds to the problem of the construction of a common world by means of inter-individual technical mediations.

I.2. Twin themes

We may note that these questions belong to two themes that are highly complementary. On the one hand there is the study of perceptual and cognitive activities with the help of deliberate variations in the technical devices that makes them possible. On the other hand, there is the study of the way in which technical devices contribute to these activities. We shall address the question of technology from three directions:

(1) The tools that are taken in hand
(2) The inscriptions of the cognitive activity in the technical environment
(3) The technical mediation of social interactions

At the same time, the TVSS suggests a way of studying these questions that we shall decline in accordance with two major principles.

I.3. The principle of double description

The sensory substitution systems such as the TVSS thus make it possible to observe, in the adult, the genesis of a novel prosthetic perceptual modality; this means that, by contrast with the study of our natural perceptual modalities which are put in place from early childhood, here we can make an association between a first-person phenomenological description of the genesis of lived experience, and a third-person psycho-physiological explanation of the corresponding perceptual capacities.

I.4. The principle of minimalism

To the extent that this novel perceptual modality is made possible by a technical device, we can deliberately vary the device in order to examine the way in which the lived experience and the resolution of the perceptual task are affected. To this end we have employed a deliberately minimalist method in which the repertoires of action and the sensory returns are drastically reduced to a bare minimum. 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. Susbsequently, we have progressively complexified the device in order to examine how the perceptual activity is transformed.

We shall rapidly describe the main results of this method.

II. Elements of cognitive technology

II.1. The tools in hand.

II.1.1. Spatial perception

In order to study the way in which the use of a tool can lead to the constitution of an encompassing distal space, we have 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.

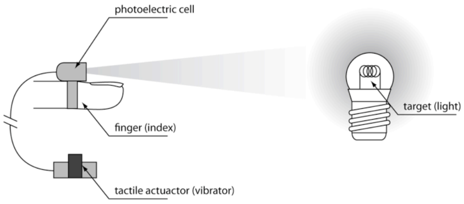

Fig. 1. Distal perception glove

At each moment in time, the subject (who is blindfolded) thus receives only a 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. Initially, the subject only perceives a succession of tactile stimuli which accompany his movements. But quite soon, as he becomes familiar with the device and starts to master it, he no longer notices these sensations which are replaced by the perception of a target at a certain distance in front of him. Here, it is quite clear that perception cannot be grounded merely on an internal analysis of the sensory information; the latter is simply a temporal sequence of all-or-nothing 1's and 0's which has nothing intrinsically spatial about it.

In such conditions of minimal coupling, it is quite easy to replace the physical reality which triggers the tactile stimuli according to the orientation of the photo-electric cell, by a digital motion capture device placed on the finger which defines the position of a receptor field in a virtual space. In the situation defined by this system of minimalist perceptual supplementation, the passage from the real world to a virtual world makes practically no difference to the subject (Thouvenin et al., 2003). The advantage is that in a virtual environment it is far easier to record the perceptual trajectories, and also to modify the conditions of coupling by changing, for example, the shape, the arrangement or the number of receptor fields.

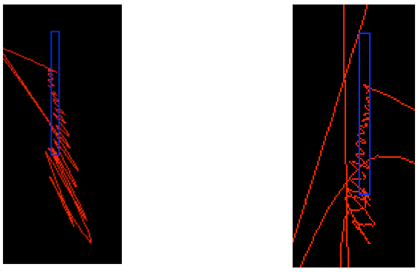

Fig. 2. Projection of the pointing movements on 2 planes which include a luminous target.

In order to maintain the perception of a target placed in front of him, the subject must act continually, moving the photo-electric cell so as to aim at the target in different ways. As soon as the movements stop, the perception disappears. This can easily be understood if we look at things from the point of view of the subject. If he is immobile, there are only two possibilities: either he receives a continuous stimulus, or he does not. If he is pointing away from the target, he has only the memory of a perception which fades away. If he pointing at the target, he receives a continuous stimulation – but this does not give rise to the perception of an external object. Spatial perception requires the *synthesis* of a temporal succession of actions and sensations. The spatial exteriority of the target can only be constituted by the possibility of freely and reversibly coming and going around it, alternately leaving and refinding contact with it (Poincaré 1905, 1907). The target is localized in direction and depth when the law governing pointing towards it is mastered. This is a good illustration of what Kevin O'Regan has called a "law of sensori-motor contingency" (O'Regan & Noë, 2001). Any given position of the target corresponds to a particular *sensori-motor invariant*, i.e. a *law* relating sensory feedback to the actions performed; this law itself is stable over and above the constantly varying actions and sensations.

II.1.2. Active perception. Enaction

Perception depends not only on sensory input, but just as much on the capacity of the lived body for *action*. 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. This conception of active perception can be schematically illustrated as follows:

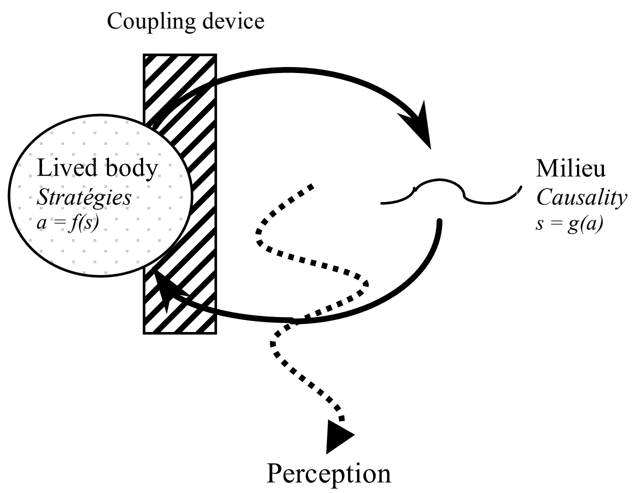

Fig. 3. Scheme of sensori-motor coupling. The system of prosthetic perception is a "coupling device" which modifies the lived body by defining the repertoires of actions and sensations which are available to the subject. Via the environment, the actions "a" give rise to sensory feedback "s" : s = g(a) ; concomitantly, the organism implements a strategy for generating its actions and modulating them as a function of its sensations : a = f(s).

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 organism. In this conception of perception, there is an important distinction to be made between "sensation" and "perception". The "sensation" is defined as the sensory input delivered to the organism; this is quite different from the full "perception", which is based on the law defining the sensory feedback for a full range of performed actions.

These considerations apply equally to natural vision. The latter requires a functional eye, but also the activity of ocular muscles which produce micro-saccadic movements (on a time-scale of 10-20 milliseconds). If the eye is completely immobilized, it appears that vision is no longer possible: the perceived image fades away in a few seconds (Ditchburn 1973, Steinman 1990). The same is also true for touch, which only gives rise to the perception of *objects* if there are constant exploratory movements. We insist again on the fact that when attention is focussed on the perception of an object, the *sensations* delivered by the coupling device (be it natural or artificial) disappear from consciousness. Thus, when we perceive a stable object at a certain distance in front of us, by using our eyes and their movements, we have absolutely no consciousness of the variable sensory stimuli on our retina.

We may note that the experimental situation we have proposed suggests an approach for understanding how, in general, the space of our perception is constituted. At the beginning of the experiment, the blindfolded subject only perceives a temporal succession of sensations on the hand that holds the tactile stimulator. This sensory input does not have any spatial value. The subject certainly has an idea about his bodily space and the world which surrounds him, but there is not yet any spatial perception associated with the device. It is only when the subject masters the situation, that is to say that he succeeds in reliably controlling the sensory feedback by his actions, that he has the feeling of being in front of a target situated in a space that encompasses both the target and the point of view on that target. It is thus by means of his perceptual activity that the subject constitutes the space of the target and of the movements of his point of view (the captor at the end of his finger) with respect to that target. There is only a space of perception if the actions are reversible, and if they can be composed. Following Poincaré, the space is constituted as a group of continuous transformations (a Lie group). The dimensions of this space depend on the variety of non-colinear actions that the subject can perform.

If the subject stands upright in the same place, and can only perform rotations at arm's length (without translations), he can maintain a sense of the exteriority and the orientation of the target, but it is no longer possible to localize the distance of the target; *depth* has disappeared from the perceived world (Lenay 1997). Thus, there is only one and the same single space for our actions and our perceptions, for our body and for our consciousness.

Does this means that we adopt an idealistic monist position (close to that of Berkeley for example), which reduces all objectivity to its perception? No, that is only half the story. The world is constituted, certainly, but it is constituted *concretely.* The constitution of lived space is concrete, produced by an embodied subject, deployed in the world and not merely in a spiritual part as opposed to a material part.

Does this mean then that we adopt a materialist monist position (close to Gibsonian ecological theories of perception)? No, because that would only be the other half of the story. The world is concrete, certainly, but it is concretely *constituted.* Indeed, space is not given in advance, it does have to be constituted. We do not start from an objectively determined physics in order to understand how it can subsequently be perceived.

II.1.3. Technical mediation

A perceptual supplementation system is a device which performs an artificial coupling between an organism and the environment to which is gives access. If we examine carefully the whole range of prosthetic devices that have been developed for handicapped persons, we find that there is no clear borderline between specifically prosthetic devices and technical devices in general. This is one of the reasons why the wider concept of "perceptual supplementation" seems to us more appropriate than the term "sensory substitution"[4]. For example, Braille characters can already be considered as a form of visuo-tactile substitution, since the letters of alphabetic writing (visual information) are converted into combinations of six tactile points in a domino format (tactile information). But if we admit that, then we have to recognize that phonetic writing is itself already a visuo-auditory substitution, since it consists of converting the sounds of speech into visual stimuli. The blind man's cane can be considered as a tactilo-tactile substitution since it enables the user to feel, thanks to vibrations in the palm of his hand, the points of contact that are experienced as being situated at the end of the cane. But this is the case for all hand-held tools (screw-driver, hammer, sword,….). Spectacles are prosthetic devices for correcting defective vision, but their functioning is similar to that of a magnifying glass, an astronomical telescope, or an optical microscope all of which aim at augmenting our visual powers. And by the way, practically all the systems of "sensory substitution", whether or not they are invasive, can equally well be used in the context of a project aimed at augmenting human capacities (vision with wave-lengths beyond the spectrum of natural vision, systems for control at a distance, etc.). Sensory substitution systems only carry to an extreme much more general principles concerning the functioning of tools – and thereby serve to render these principles manifest.

In general, the lived body of an organism defines the system of possible actions and sensations, and thereby defines the accessible perceptions. Prosthetic devices, like any tool that can be grasped, transform the possibilities of the lived body and open new fields of possible perceptions. Perceptual supplementation systems therefore allow a fundamental study of both perception in general, and of the role of technical mediations. On one hand, they provide an experimental access to important questions such as the consciousness of objective things in a space "out there", because they make it possible to follow and to reproduce the genesis of this consciousness in the adult. On the other hand, by allowing systematic modifications in the capacities to act and to feel, they allow a precise analysis of the way in which technical mediations are constitutive of perceptual activity. Perceptual supplementation systems can play a paradigmatic role, because they allow for clear and complete control of the repertoires of sensations (the distributed sensory stimuli) and of actions (the possible movements of the receptor fields).

It is only through this technical mediation that the user is able to constitute the new perceptual contents and perceptual space. The technical mediation "creates a possibility", but it does not "determine" any particular content; the technology is enabling but not determining.

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. In these examples, the technical mediation highlights features that are actually quite general in the use of tools of all sorts.

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[4] Lenay, C., Gapenne, O., Hanneton, S., Marque, C. & Genouel, C. 'Sensory substitution : limits and perspectives', in Y. Hatwell, A. Streri & E. Gentaz (eds) *Touching for knowing, cognitive psychology of haptic manual perception*. Amsterdam & Philadelphia: John Benjamins Publishing Company. (2003).

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" [Merleau-Ponty 1945 : 167]. 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.

II.1.4. In hand / put down

In order to fully understand what is involved in the use of tools in general, and prosthetic perceptual devices in particular, it is important to make a thematic distinction between two "modes of existence" of tools: "in hand", and "put down". A tool is in the "in hand" mode when it is grasped and used; it is then "interiorized" and becomes a part of the lived body, to all practical intents and purposes as much as the natural biological organs of perception and action. Just as my own lived body is invisible to me, and appears rather in the guise of a set of capacities for action, so a tool in the "in hand" mode disappears from my consciousness, which is focussed instead on what I can do *with* the tool. However, unlike organs such as the eyes or the hands, a tool can also exist in a second mode, that we may term the "put down" mode. It is in this mode that human beings can repair tools, make them, exchange them, and above all deploy their imagination to *invent* new tools. To sum up: in first "in hand" mode, a tool is *constitutive*, giving rise to a capacity for perception; but by the same token, in this mode the tool itself is not perceived. I do not perceive my spectacles when I am wearing them, just as I do not perceive my eyes, or my optic nerve, or my visual cortex. In the second "put down" mode, the tool is *constituted*; it has now become an object that I can perceive in the space in front of me.

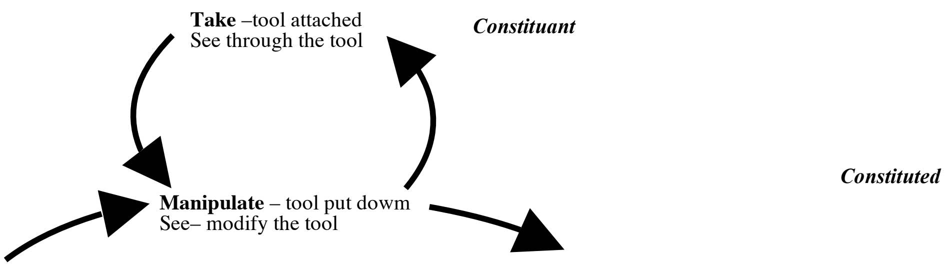

Fig. 4. Model of the tool states. The tool in the « in hand » mode is invisible because it is the means for seeing. The tool in the "put down" mode can be perceived and exchanged.

The fundamental characteristic of tools is that there is a constant back-and-forth movement between these two modes. For example, when I am driving a car my experience oscillates rapidly between moments when the car is an invisible part of my lived body through which I perceive the road I am driving along; and other moments when the car is separate from me so that I can focus my attention on it – for example when I look at the dashboard or fix my safety-belt.

II.1.5. The internal vs external distinction

The distinction between the « internal » and the « external » is continually modified, and must thus be defined functionally:

- "Internal", in the case of perceptual activity, corresponds to everything which moves together with my point of view ;
- "External" corresponds to everything which is constituted as a stable object, and which therefore functions as a reference with respect to which my point of view changes its position.

In a way, this approach is neither externalist, nor internalist, because the space of perception and its contents are constituted in the relational coupling between the living organism and its environment. It is only on the basis of this relation that there is a perceptual space, i.e. a lived world for the organism. Space is the form of the coupling, the structured domain of constitutable invariants.[5] However, if we situate ourselves in this space in order to distinguish and to locate the point of view with respect to objects, then our approach becomes clearly externalist because objects are not perceived as being behind the point of view, but as being clearly in front of it, in the very same space where the point of view moves.

II.2. The inscription of cognitive activity in the technical environment

II.2.1. Shape recognition – the Tactos system

The perceptual actions of a subject correspond to movements of his "point of view", i.e. the site from which the object is perceived. According to the coupling device that is employed, this site can be different from that where the sensations are delivered. We will illustrate this point by another system that we have developed with the aim of providing blind persons with access to digital forms present on a computer screed. The "Tactos" system (Hanneton, 1999) 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.

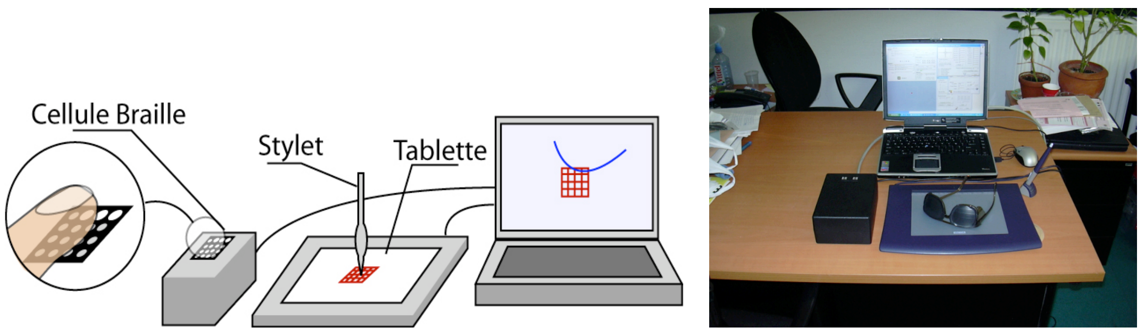

Fig. 5. Tactos system including the stylus and the graphic tablet, the computer and the Tactos software, the braille piezoelectric cells matrix

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[5] A corollary of this relational definition is that other forms of coupling would give access to other forms of space with different dimensionalities. This does indeed seem to be the case, for example infra-atomic physics when new instruments of coupling (such as particle accelerators) give access to new structures of invariants.

The cursor here corresponds to a small 4 x 4 matrix of 16 receptor fields. 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 this does not hamper the perception of the forms.

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. Even in this minimal version, we observe that subjects are able to perceive forms. 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 analyse this activity. This is what we have called "perceptual trajectories" (figures 6a et 6b). (Lenay, 2002, Sribunruangrit 2003).

Fig. 6a

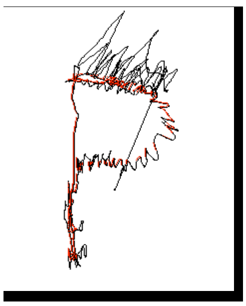


Fig. 6b

Fig. 6. perceptual trajectories with Tactos

These *perceptual trajectories* reveal several behavioural invariants. The subject starts by making wide exploratory movements; but as soon as a contact with the shape is obtained by crossing a line on the figure to be perceived, the subject rapidly converges on a strategy of *micro-sweeps,* oscillations of small magnitude around the source of stimulation. This is indeed an operation of localization. In these experiments, we observe that the imprecision of proprioceptive information[6] and/or memory limitations are such that if the subject moves too far away from the figure, he becomes lost and wanders around trying to recover the last point of contact. The subject does not seem to have access to the absolute position (in x-y co-ordinates) of the stylus on the tablette. He perceives only the direction and the amplitude of his movements, and even then with rather low precision. In these conditions, the immense

[6] Wann J.P. and Ibrahim S. 'Does proprioception drift?' *Experimental Brain Research* 91, 162-166, (1992).

advantage of the "micro-sweep" strategy is that it enables the subject to remain robustly in contact with the figure.

However, the micro-sweep gesture is not in itself sufficient to provide a perception of the figure. With unlimited memory and precise proprioception, we might envisage a strategy of "scanning" the figure, i.e. "mapping" the positions of all the points. The subject might then be able to calculate a "mental image" of the figure to be perceived. However, the incapacity of the subjects to identify the absolute positions in (x,y) renders this strategy ineffectual; and in fact it appears that the subjects do not proceed in this fashion.

The second characteristic of the perceptual trajectories therefore consists of a tangential displacement, following the local direction of the segment of the figure. Because of the limitations of the single receptor field, it is not possible to reliably follow the segment; inevitably, the subject ends up by drifting off the figure on one side or the other. If the subject had been attempting to follow the segment directly, the snag is that he then does not know on which *side* he has left the form, and consequently there is a high risk of becoming seriously lost. The strategy generally adopted, illustrated in Figures 3a and 3b, is thus a combination of the two elementary gestures: firstly, a rapid perpendicular oscillation which makes it possible to verify the position of the segment in this direction, and to "centre" the oscillations; secondly, a more gradual tangential movement which aims at following the whole length of the segment. This overall movement implements a second-order anticipation, based on a stability in the temporal frequency of the resultant stimulations.

This progressive exploration of the current segment is continually adjusted, taking into account possible surprises in the contour. Whenever contact with the figure is lost – for example, because of a sharp angle in the figure – the stylus backtracks, tries a new direction, and as soon as the new micro-sweep gives a regular stimulation again, continues on its way…. until the next detour. Each of these tangential directions is the confirmation – or the refutation – of an anticipation concerning the stimulations expected from the micro-sweep. We propose to consider that this stage corresponds to the recognition of "features" which together make up the perceived figure as a whole. Thus, the perceptual trajectories are both **recognition** and **enaction** of the figure. As in the phenomenological perspective, perception consists of succeeding (or failing!) to satisfy an active anticipation.

II.2.2. Immersion in the space of action and perception

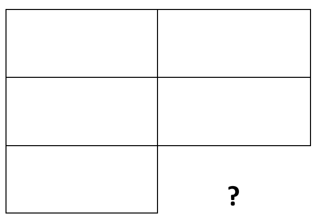
The proprioceptive perception and memory of absolute position is too imprecise for the subject to be able to plot the positions of the hand which holds the effector (mouse, stylus…) in egocentric X-Y co-ordinates. It is thus quite impossible for the subject to scan the whole field of the screen, and 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 he is immediately "lost", and cannot even proprioceptively return to the last point of contact with the form. The subject starts out with large-scale exploratory movements, but as soon as he obtains a contact with a line, he converges to a *micro-sweeping* movement of small amplitude around the source of stimulation. This can be understood as essentially 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. At the same time, this micro-sweeping movement enables the subject to identify his own position, not in absolute co-ordinates but relative to the form that he is exploring and perceiving.

This localization of the point of action is the condition for being able to project oneself into the space created by the technical mediation. This is what happens, for example, in the now common-place use of a mouse to move a cursor on a computer screen. The fact that the cursor is blocked by the edge of the screen, whereas the hand can freely continue its movement, is not a hindrance but actually a help because the user defines his actions not by his hand, but by the cursor that he sees on the screen.

If the action is properly characterized not as the movement of a site of inscription, but rather as the movement of a site of perception (in general, a "point of view"), then we can consider that there is "immersion" in an encompassing space. The point of perception is then situated in the same space as the perceived objects. If the point of perception is blocked, the user will understand that he himself is blocked in the virtual space. For example, in a video-game of subjective action, when a panoramic movement is blocked by an obstacle even though the player continues to push on his joystick, he will know that he is blocked and will seek to skirt around the obstacle by taking another route from the place where he was stuck.

II.2.3. Graphic reason

The importance of the technique of writing, as a basis and an instrument of thought, is well recognized.[7] Besides current research on morpho-dispositional semantics or *Information Visualisation* [8], we will just recall the pioneering work of Jack Goody[9]. According to Goody, graphical inscriptions are not merely ways of memorizing or expressing existing knowledge; beyond that, by their very structure, they participate in the production of new knowledge. Thus, Goody attempted to define more precisely how it is that the use of writing exerted an influence on congitive structures. These new conceptual categories that are made possible by the technique of writing define what we may call "graphic reason". Goody cites as prime examples the formula, the list and the table. The idea of a "graphic reason" is attractive because it makes it possible to account for numerous cognitive practices. For example, we may note that the very fact of drawing a table seems to induce a necessity to fill in all the empty cells that it defines :



But where exactly does this necessity come from ? If the existence of an empty square is simply the result of the structure of space, why should it impose itself on thought as a lack that must be filled ? If we make a distinction between, on one hand, cognition as a system for the manipulation of representations that are situated in the brain, and on the other hand the layout of inscriptions in the external space, why should this spatial structure of the objects bear the cognitive structure of an act of reason? Should it be admitted that the perception of

[7] For example, see the classic work of Leroi-Gourhan A. (1964), Derrida J. (1968) Auroux S. (1994), Stiegler B. (1994).

[8] This term was first used in 1989 by Robertson, Card, et MacKinlay (1999). See also Spence (2001).

[9] Goody (1977). We may also recall the previous work on semiology by Jacques Bertin (1967).

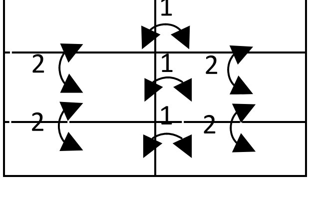
the table corresponds to the activation of representations that are themselves arranged in an internal space of representation? That would be complicated, insufficient and useless. Complicated because one would have to postulate a doubling up of space: internal spaces of representation and external physical space. Insufficient because it would still have to be shown how these internal spaces might be able to guide a process of reasoning. And finally useless, because if external spatial inscriptions could only become effective if they were reproduced internally, it would become impossible to understand how the development of our knowledge could actually have been linked to the availability of these inscriptions.

We much prefer an externalist approach where the concrete substrates, such as written inscriptions, can themselves directly function as the substrate of our cognitive activity.

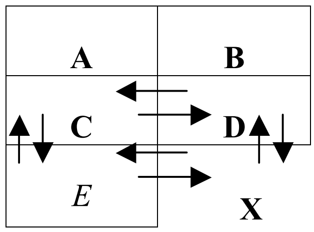
But how is it possible to conduct an empirical study of this question? How is it possible to observe perceptual activity finely enough so as to be able to recognize the cognitive operations that it may bear? The classical techniques of following eye movements give relatively limited results, because of the extraordinarily rich synthetic capacity of the retina in the human visual system. A single fixation is sufficient to capture an image that is already highly complex; and the bulk of the data processing is done in the central nervous system in a way that is not amenable to observation. This is where the systems of perceptual supplementation have an immense advantage. By strictly controlling the sensory input at each instant and the exploratory activities that are allowed, these devices make it possible to *externalize the perceptual activity.* In fact, in the extreme minimalist case, these conditions make it possible to set up a form of externalisation of the cognitive activity itself, in the play of interactions with the spatial organization of the inscriptions. The cognitive activity, like the perception, is deployed *in situ*, in the very same space and duration of the sensori-motor coupling between the organism and its environment.

The constraints and substrates of the cognitive activity are fundamentally related to the mode of constitution of the space, which is also the constitution of the spatiality of the actions. The actions which scan the space must be reversible, and must be composable according to the dimensions of possible displacements – typically translations in a 2-dimensional space. This make it possible to define a symmetry of differences in the two directions of the plane.

The relative positions of the inscriptions make it possible to define between them relations of ordering or categorisation, of opposition or proximity. The main constraint is that the items of one column share the same difference (1) with items in the other columns; and that items on the same line share the same difference (2) with items on the other lines. The origin of this is neither more nor less than the topological and metrical constraints on reversible displacements in this space.



An important cognitive operation that is supported by the table is the possibility of designating and determining an ignorance. Given the constraintes of the bi-dimensional euclidean space in which the table is inscribed, if a cell is empty it does not thereby cease to exist. And if a cell is missing, it is missing spatially *and* cognitively because it corresponds to an absence of reversibility in reading as an activity, both perceptually and conceptually. The empty cell must exist by virtue of a perceptual necessity, i.e. the necessary reversibility of the perceptual trajectories. And this ignorance is sufficiently identified, since the table defines a research programme for filling it: find a term which verifies the systematic differences in both the lines and the columns, i.e. find a term which makes it possible to compose the displacements in the different directions of the table so as to move reversibly between the positions/terms D and E, passing indifferently by C or by X. If this were not the case, it is the very coherence of the bi-dimensional space itself which would be threatened.



By contrast, if the celle X is both accessible and filled in, a synthesis which is both spatial *and* cognitive becomes possible, and one can for example determine the relations between the two variables corresponding to the two dimensions of the table.

II.3. Interpersonal technical mediations

II.3.1. Shared emotional and aesthetic values

Here again, the systems of perceptual supplementation will serve as an illustration and a guide. It is notable that although the early sensory substitution systems such as the TVSS were a success from the psychophysical point of view – as described above, they conferred remarkable capacities for the perception of forms – they have been an economic and social failure. The reasons for this are not hard to understand. When they began to discover this new sort of access to objects situated at a distance in space, the blind persons concerned declared that they were disappointed – and on top of that, they were uneasy about appearing as "cyborgs" in the "eyes" of others. Devices such as the TVSS do make it possible to perform certain tasks which would otherwise be impossible. But this does not satisfy the deepest wishes of a blind person who engages in this sort of experiment. At the existential level of personal self-accomplishment, a blind person does not really need to perform this sort of task for which vision is indispensable. In order to be motivated to invest fully in visual tasks, the latter would have to contribute some meaningful progress at the level of lived experience. What a blind person who accepts to undertake the somewhat arduous appropriation of this sort of coupling device is looking for, is something like a direct appreciation of what he hears sighted persons going on about: the *marvels* of the visible world, the *joys* of this realm of existence which is unknown to him or which he has lost. Now in fact there are numerous differences between this sort of artificial coupling with the environment, and the mode of coupling of natural vision: there is no colour, there are only a small number of points in the image, the movements of the camera are rather clumsy and limited…. It is necessary to take into account the fact that such artificial devices never exactly compensate for a deficiency, but rather introduce new and original perceptual modalities.

Each time that a tool is grasped and appropriated in the "in hand" mode, it transforms our capacities to act and to feel, and it opens up a new space of possible perceptions. Whether one grasps a stick or a telephone, whether one puts on a pair of skis or skates or spectacles, whether one manipulates a computer mouse or the bow of a violin,…. in each case the technical mediation gives rise to a specific set of sensori-motor invariants which constitute a specific domain of perception. Now, for each of these examples of technological devices which have been socially adopted, we know that the original domains of possibilities that they give rise to are qualitatively and emotionally differentiated: the *style* of a skating figure, the *sonority* of a Stradivarius,….. With the TVSS, when one shows a person who is blind from birth his own image, or the image of his wife, the result is of no particular interest to him. When blind students were shown the images of nude pin-ups, they were totally disappointed: their perception did not convey any emotion. There is indeed the constitution of an object, a capacity for discrimination and categorization; but there is no emotional value attached to these percepts. What seems to be cruelly lacking in this new perceptual modality are the *qualia*, the *values* of the perceived entities (Bach y Rita 1997). The question of the emotional value attached to the percepts made possible by a prosthetic device cannot be simply reduced to the existence of a neuronal circuit connecting to a brain mechanism for natural emotions. Or at least, if such a circuit does exist, it would be necessary to understand how it can be created in a situation where it did not pre-exist. It is therefore necessary to try and understand the conditions under which a system of specific values and tastes can be constituted, learned and appropriated for each new coupling device.

We can put forward the hypothesis that such values may emerge from a common history, built in the course of interactions between several subjects in a common environment defined by the same means of access [Lenay 2003]. What then are the conditions for the *collective* constitution of emotional values in *communities* which share the same means of perceiving and interacting? It is not possible here to cover the immense psychological, sociological and philosophical literature on these questions. We shall rather take advantage of a specific *minimalist* experimental and technical situation in order to initiate a fundamental study of prosthetic perceptual interactions.

We intend here to discuss two of the conditions for the genesis of emotional values. Firstly, the recognition, by means of a technical mediation, of the presence of another intentionality, of another perceiving subject. Secondly, the recognition, in the context of such an interaction with another person, of the features of the prosthetic image that each subject presents to the other.

II.3.2. A study of perceptual crossing

The lived experience of the presence of others seems certain and directly perceptual. But even within the framework of ecological theories, recognizing an intentional subject remains a decision which occurs *after* the perception of determinate forms and pattern of movements. In the same way as for representationalism, the recognition of another subject occurs as a result of an inference (Gergely & Csibra, 1997; Gibson, 1963). Here, we suggest that the *direct* perception of others as intentional beings is possible in situations of mutual recognition, such as when we catch someone else's eye (e.g., Argyle & Cook, 1976, Sartre, 1943). A minimalist experiment can be designed to give an empirical content to this hypothesis.

Twenty participants (10 females and 10 males) took part in this experiment. Pairs of blindfolded participants (P1 and P2), placed in separate rooms, interacted via the experimental device "Tactos" that we have described above. The position of each participant corresponded to the position of a receptor field along a shared line (with the ends joined to form a torus) which contained two additional objects: a fixed object and a mobile object. Each time a participant encountered an object or the partner's receptor field, he received an all-or-none tactile stimulation.

The task for the participants was to click whenever they think that they have encountered the other participant's receptor field. In order to make sure that the mobile object had objective trajectories of displacement similar to those of the other participant's receptor field, it was attached by a virtual rigid link at a distance 50 pixels from the centre of this receptor field.

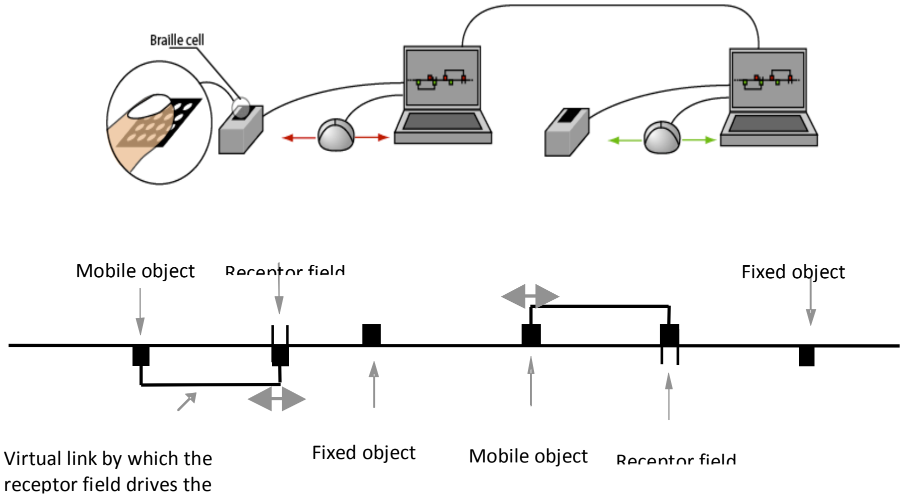


Fig. 9. Illustration of the one-dimensional space of interactions. Each participant drove his /her receptor field with his/her mouse. He/she received an all-or-none tactile stimulation when the receptor field crossed an object (in black): fixed object, other participant's receptor field, or the mobile object attached to this receptor field.

The only difference between the mobile object and the partner's receptor field was that when participant 1 explored participant 2's mobile object, participant 2 did not receive any tactile feedback; but when one of the participants explored the other participant's receptor field, both received tactile stimulation. Despite the absence of any difference in the sensory stimulations, the participants were able to recognize when the succession of tactile stimuli they received was due to their active exploration of another participant rather than the fixed or the mobile object.

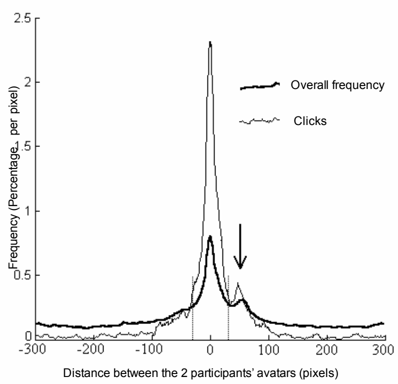


Fig. 10. Frequency distributions as a function of the distance between the 2 participants.

The thick line represents the overall unconditional frequency distribution of stimulations received. The thin line represents the distribution of distances when the participants clicked. In both cases there is a clear peak at a distance of 0 pixel i.e., in situations of mutual perception; showing the existence of an attractor around this point. The slight subsidiary peak at a distance of 50 pixels, marked by an arrow, corresponds to the mobile object.

Thus, participants interacting in a minimalist environment were able to recognize when the succession of all-or-none tactile stimuli they receive are due to meeting the receptor field of another participant. They were able to do so even though there was absolutely no difference in the stimuli themselves (simple all-or-none signals in all cases) and even though the structures of movement were identical. This minimalist paradigm forces an externalization of the perceptual activities. It allows the recording and analysis of the participants' trajectories of displacement. Calculations performed on these trajectories revealed that the large difference observed between clicks on the receptor field and clicks on the mobile object (65.9% vs. 23.0%) must be attributed to the conjoint strategies of movement, which are such that stimulations associated with the mobile object were much less frequent than those due to the receptor field (52.2% vs. 15.2%). The success in the task, that is, the recognition of the presence of others does not correspond to recognition as categorization of the received stimuli. If the participants succeeded in the perceptual task, it is essentially because they succeeded in situating themselves in front of each other. The recognition thus corresponds primarily to an active discrimination: the capacity to build an attractor in the collective perceptual dynamics.

The main condition that creates such an attractor of the situations of mutual perception is the following. My partner, just like me, is seeking to perceive me. That is, he is looking for an invariant in his sensorimotor dynamic (being able to maintain an oscillation around a spatial singularity). The active perceptual activities attract each other just as in everyday situations two people catch each other's eye. The perception of the perceptive intentionality of another subject corresponds to a characteristic pattern in the conjoint sensorimotor dynamics: an attractor with no spatial stability. The gaze of the other maintains its presence but resists attempts at a definite spatial localization.

The results of this experiment suggest that I can perceive another intentional subject, not merely through any determinate pattern of movement, but rather directly as a perceptual activity oriented toward my own perceptual activity.

It is not irrelevant, given our current concern for emotional values, to note that the participants in this study declared that they were *intrigued and amused* by this experiment, in spite of the radical poverty of the sensory data. The meaning and the emotional quality of the percepts do not necessarily depend on the richness of the sensory input, but rather on the dynamics of the interactions, particularly when they give access to the feeling of the presence of another intentional subject.

We therefore consider that affording the possibility of perceptual crossing is a key element for the success of new interactive devices. We may now go on to ask whether the body-image that I present to the other person when I use this sort of device, but which I do not directly perceive myself (just as I do not see the spectacles I wear), can nevertheless be accepted and recognized by me. Does the way in which the other perceives me give me the means to guess the image that I present to him?

III Epistemological framework

III.1. Externalism

Classically, science and technology are opposed to each other on the grounds that on one hand science studies natural phenomena, and on the other hand technology produces new things, if possible on the basis of scientific knowledge. Thus, technological developments are considered to be the result of applied science. If we were to adopt this framework, "cognitive technologies" should correspond to "applied cognitive science". The aim of cognitive science would be to gain knowledge concerning "natural cognition", and this knowledge could then be used to construct technologies which would perform cognition[10].

Our approach, by contrast, is almost exactly the opposite. Not only do we consider that an accomplished science of natural cognition does not yet exist; even more to the point, we think that human cognition has always been an "artificial cognition", supported by tools and technological environments that our parents have bequeathed to us and which we will pass on to our children, as an integral part of human culture and history. The tool, rather than being thought of as a means for reproducing "natural" internal functions that are already present, is far better understood as constitutive of novel intellectual operations and possible realms of lived experience. Human cognition is originally prosthetic, ever since it is characteristically human. 2 million years ago, even before the advent of *homo sapiens*, *homo habilis* used tools that were produced by his ancestors and which he left to his progeny. This is why we say that "Technology is Anthrophologically Constitutive" (the TAC thesis)[11].

Our scientific aim is thus a fundamental and systematic study of technical artefacts, and the way that they impact on human experience. Now the coherence of such a scientific research programme requires a strong epistemological position: we have to consider that psycho-logy and techno-logy are **general, fundamental sciences**.

There is indeed a classical epistemological position according to which psychology is a "special science", i.e. a science which only occupies a limited, secondary region in the whole set of phenomena. On this view, a science such as physics is considered to be a fundamental science, because everything that exists belongs to the physical world and must therefore obey its laws. This epistemological position has two consequences. The first is that we are immediately inveigled into interminable debates on supervenience, or the reductionism of psychological phenomena with respect to the laws of physics[12]. The second consequence is that if one admits a precedence of physical science, one is necessarily lead to a representationalist conception in psychology, a conception which makes it impossible to understand the effectiveness and the historical role of cognitive technologies.

The point here is that if one once admits that "space" is objectively given in advance, and that living organisms and their consciousness are situated within this pre-given space, then the separation between subject and object is also ineluctably given in advance. On this

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[10] This was the ambition of « Artificial Intelligence », which was based on the computational theory of mind according to which cognition consisted of the internal manipulation of symbolic representations.

[11] Bernard Stiegler, *La technique et le temps*, Paris, Galilée, 1994

[12] The **special sciences** are those sciences other than physics that are sometimes thought to be *reducible* to physics, or to stand in some similar relation of dependence to physics as the "fundamental" science. The usual list includes chemistry, biology, neuroscience, and many others. The status of the special sciences, and the explication of their precise relationship to physics, is a matter of much controversy in philosophy of science. Some, famously including Jerry Fodor, hold that the special sciences are not in fact reducible, but *autonomous*: they have laws of their own, which could not be deduced from the laws of physics, even in principle. Others, like W.V.O. Quine, are well-disposed towards reductionism, and may even see physics as "including" the special sciences, almost as subdivisions. Most contemporary philosophers of science, if they are not committed to reducibility, believe that the facts of the special sciences at least depend on the facts of physics by *supervening* on them.

view, in order to understand perception the task is to explain how an organism situated here can perceive things that are situated “out there”, outside of the organism. One will thus be lead to seek for something in the brain-states of the organism (“mental states”, “representations”,…) which is located spatially within the organism, and which “corresponds” to the objective objects of perception. It is then necessary to imagine that the lived experience of a subject can be attached to some local substrate, quite distinct from the object of perception itself. This is the position that we call “internalist”; we claim that this position is riddled with aporia (duplication of the external space by one or more internal “representational spaces”).

However, if we take a radically different option (as proposed here) and consider that *all* phenomena – be they physical, biological, sociological, historical or linguistic – are always phenomena *for a conscience*, then they must all be amenable to a *psychological* description. In this approach, psychology is a general science, i.e. a point of view on the totality of reality – which is not to say that this discipline should be dominant or totalizing. Rather than fragmenting reality into diverse regions according to the disciplines, we consider that each discipline is a sort of point of view on the totality of reality, and that these points of view can intersect. Thus, physics is just as much a part of psychology as psychology is a part of physics. In a similar vein, one could very well consider that linguistics is a fundamental science, because there is no know object of science that is not given in language (or at least in a semiotic system); or that history is a fundamental science because every phenomenon available to human beings is a historical event; or, again, that sociology is a fundamental science because everything that can be thought of can only be conceived on the basis of rules, norms and idealities that are socially determined; and so on.

Now if we wish to consider psychology as a general science, one of the first things that will have to be done is to account for the constitution of objectivity, and therefore of the space of physics. We have examined above (in section *II.1.2.*) the constitution of the space of perception, which comes about through the coupling between the organism and its environment. “Space” corresponds to the Lie group of displacements which are reversible and non co-linear. This is how we can account for the enaction of space, for the constitution of objects situated in this space, and for movements of the point of view relative to these objects. Each position, each object corresponds to a sensori-motor invariant allowed by the coupling device.

This naturalization is not a reduction to physics, nor a supervenience, but the explanation of the construction of the contents of experience, a construction that is both concrete and subjective. There is not representation, but rather constitution, in the sense of construction, of all the contents of consciousness.

It is thus possible, as we have done, to describe perceptual and cognitive activities according to a double perspective: phenomenological, in a first person perspective; and psychophysiological, in a third-person perspective.

This gives rise to what we call a “reciprocal envelopment”. For example, if one says on the phenomenological level that the constitution of depth has as a condition the powers and the orginal spatiality of a lived body as the possibility of engaging in depth, one can understand at the same time on the objective level that the localization of a target at a distance requires that the subject has a size and an articulated body which allow him to advance in space towards that object. To take another example, if one says on the phenomenological level that the perception of a shape corresponds to the satisfaction of an anticipation, one can understand at the same time on the objective level that the perception of this shape corresponds to the success of an overall gesture of following the contour of the shape. This is possible only because “objectivity” is itself constituted by and for a consciousness. There is nothing outside consciousness, and reciprocally the operations and contents of this consciousness can be explained by concrete operations in the realm of objectivity. For example, if I perceive an object, let us say this book place on my desk, it is not because I have a representation in my brain (how a neurophysiological state inside the brain could carry a content of consciousness different from itself, is the famous problem of intentionality in the sense of analytical philosophy). If I have this conscious perception of the book, it is because, with the concourse of my brain, my eyes, my hands, and the causality of the environment, I am able to act with respect to this object, following the rules which link my concrete actions to the flow of sensory input which ensues. It is in my concrete relation with the book that I constitute it as the content of my consciousness. And this content is not in my head, but fairly and squarely out there on the table. My consciousness of the localisation of an object is situated there where the object is, and not in my head. I use my brain to perceive (in order to define the strategies which guide my actions as a function of the sensory feedback), but my perception is not situated in my brain. The space of my consciousness, and the physical space, are fully co-extensive. We have tried to show above how cognitive constraints can be the direct expression of constitutive constraints of spatial reversibility. Material inscriptions (writing, drawings, maps, schematic sketches, etc), by spatialising thought, force it to satisfy the constraints of the constitution of that space. But that is only comprehensible because the intellectual operations (categorisation, laws of relation….) occur in the space of the table and not in a space of representation. It is the very same operations of displacement which serve both to constitute the space, and to compare the items which are inscribed within it.

We may note that there would not be much interest in mobilizing a phenomenological description if one considered that consciousness results from infra-personal processes that are not themselves conscious. In this case one would fall back into a separation between the neurophysiological and psychological domains. And in that case, in spite of all the efforts of the philosophy of mind, one would have to admit an unbridgeable "explanatory gap", because a material phenomenon such as a configuration of neuronal activity will always be radically different in nature from an experienced state of consciousness.

Even if one were to admit that there are as many internal neurophysiological differences as there are different contents of lived experience, it does not immediately follow that these internal states would be the bearers of the experiences. To do so would be to fall back into the explanatory gap between the internal state and the consciousness of an object, of space, and so on. By contrast, on the approach that we propose here, all that has to be admitted is that this internal neurophysiological structure participates in the construction of the content of experience, in the same way that bodily and technical conditions of the coupling, and the causality of the environment, also participate.

We therefore adopt an externalist approach to cognition, an externalism in the strong sense of the term, for which external technical substrates are an integral part of cognitive activity. This position is very close to that of active externalism (Clark & Chalmers 1998) and the *extended mind theory* (Clark 2003). However, our brand of externalism might be more properly termed « enactive externalism », since it concerns cognition as well as simply perception.

III.2. The principle of concrete operations

In the framework of situated cognition, the cognitive activity of one or more subjects can be understood in terms of a game of inscriptions in the environment, and perceptual interpretations of the spatial organization of objects and symbols. This interpretative activity corresponds to the active schematism (in the Kantian sense) of the determination of the object by a gestual strategy of grasping the diverse, as we have seen in detail for the recognition of shapes.

In the dynamics of coupling, the organisms ceaselessly modify the shared situation as a function of their perception of the situation. The inscriptions serve as an external memory that can be shared[13]. By their spatial organisation (as with the tables of data) or by their integration in physical processes (such as computers), these inscriptions give rise to new interpretations, which in turn lead to new inscriptions. To the extent that the subjects modify the conditions of their subsequent interpretations by their own interpretative activity, we can speak of a hermeneutical trajectory (Figure 9).

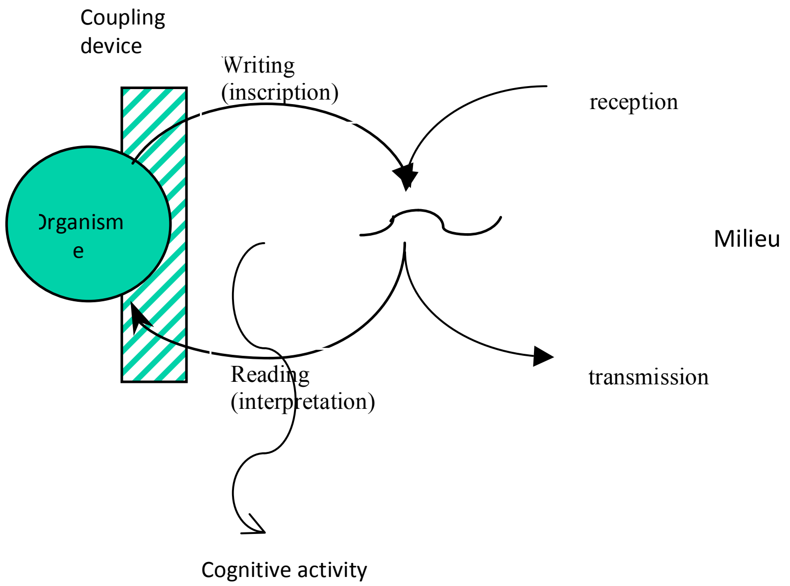

Figure 9

Learning, and the discovery of new knowledge, can be understood as the taking in hand of new tools or the development of new strategies. Through this interplay of writing and reading (in the wide sense), and by the making of tools (coupling devices) that can be taken in hand, one can account for all the concrete cognitive operations that have been observed. In fact, the power of such a dynamics is paradoxically at least as great as that of a Turing machine, which precisely defines computability by taking the model of an interplay of writing and reading an unlimited spatial external memory. Of course, we can also consider forms of "internal" writing in the brain relating to events or learned strategies. But there is no particular privilege to such internal memory compared to an external memory in the environment surrounding the organism (Dartnall, 2005).

Of course, the power of the nervous system with respect to combinations, memory, and recursivity, make it possible to imagine all sorts of internalisation of operations that can also be observed in the system of bodily relations with the environment. But, following a heuristic principle that we call the "principle of concrete operations", for every internal

[13] As for the « stigmergy » of emergent structures in social organisms, Intellectica, 1994.

operation, one can seek a chain of concrete operational events (actions, inscriptions, sensations) which would have the same functional dynamics; and conversely, this dynamics can serve as a leading model in order to identify and to understand its reproduction in the central nervous system.

For example, the capacities of anticipation or reflexion do not necessarily derive from a representational structure of the mind, but rather from the faculty of imaginative production of the content of an experience, a faculty which can be external to the organism when, in a reserved domain, one plays out or describes a situation that is past or to come – or internalised when the situations of action and perception are constructed or reconstructed in the intimity of the body.

III.3. Conclusion

Of course, this is not to say that cognitive phenomena can be entirely explained (no more that physical phenomena that we do not pretend to understand completely); it only means that their explanation will only be complete if and when we manage to externalize them in the form of concrete operations. Even if the task is probably infinite, there is here no principled line of demarcation by which one could pretend to define the limits of the domain of phenomena that can be explained. We may note, in addition, that the type of explanation that is proposed, to the extent that each time it aims at accounting for the constitution of the phenomenon in question, is in no wise a naturalisation that would "disenchant" the world. The explanation does not make the explained phenomenon disappear. On the contrary, it provides an account of its construction. The lived experience of a conscious mind does not disappear because it has been explained, as if it had been reduced to blind mechanisms that have no consciousness. In fact, the concrete operations of the construction of meaningful content are not external to consciousness itself. On the contrary, I can understand them from a first-person perspective, following the description of their phenomenological genesis, without having the need to add additional "external" causes. At the same time, we can appreciate that this genesis is also amenable to a description in third-person terms, as an operation of perception and inscription in the objectivity that we constitute and share.

When the laws of coupling make it possible to account for the constitution of space and objects, they correspond to the laws of physics. When the laws of coupling make it possible to account for the constitution of shapes and meaning, they correspond to the laws of psychology. And when the laws of coupling make it possible to account for the constitution of a common world and the institution of norms, they correspond to the laws of sociology.