Sensori-Motor Appropriation of an Artefact: A Neuroscientific Approach

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1. Introduction

The required objective for the design of a machine to be used by a human operator is its adaptation to the user's capabilities. According to this logic, the ideal system should fit perfectly into the human sensori-motor loop. The system would disappear from the field of consciousness and the operator would use it as a "natural" extension to her/his own body. In order to complete this goal we first have to know what the human capacities of appropriation of an artefact are. This chapter proposes to answer this question from a review of a series of studies in the field of psychology, neuropsychology, neurophysiology and information technologies.

We will understand that the appropriation, or ownership, is achieved not only thanks to the natural adaptation properties of the human being, but also through artificial processes designed by the HMI engineer. The human adaptation is described as involving two complementary processes, taking place in opposite directions, called *assimilation* and *accommodation* (Piaget, 1952). This adaptation occurs because the nervous system's plasticity makes it possible to integrate an artefact in the body schema (Maravita & Iriki, 2004, for a review). The fundamental aim in the HMI field is to further natural processes of adaptation via an implementation of artificial ones. Like natural processes, artificial ones can be carried out according to two directions. On one hand, the way in which the machine works can be brought closer to the human skills (Rybarczyk et al., 2001). This approach is called anthropocentric. On the other hand, the individual her/himself can be modified in order to plug electro-computational devices into the nervous system and to become a cybernetic organism or *cyborg*. This last research area is not science fiction anymore, but has already demonstrated its advantages in the field of assistive technologies (Hochberg et al., 2006) or in enhancing the human capabilities (Warwick, 2009). Figure 1 represents the sensori-motor appropriation of artefacts such as introduced here. The following sections of this chapter will describe in detail each module through an explanation supported by neuroscientific evidences.
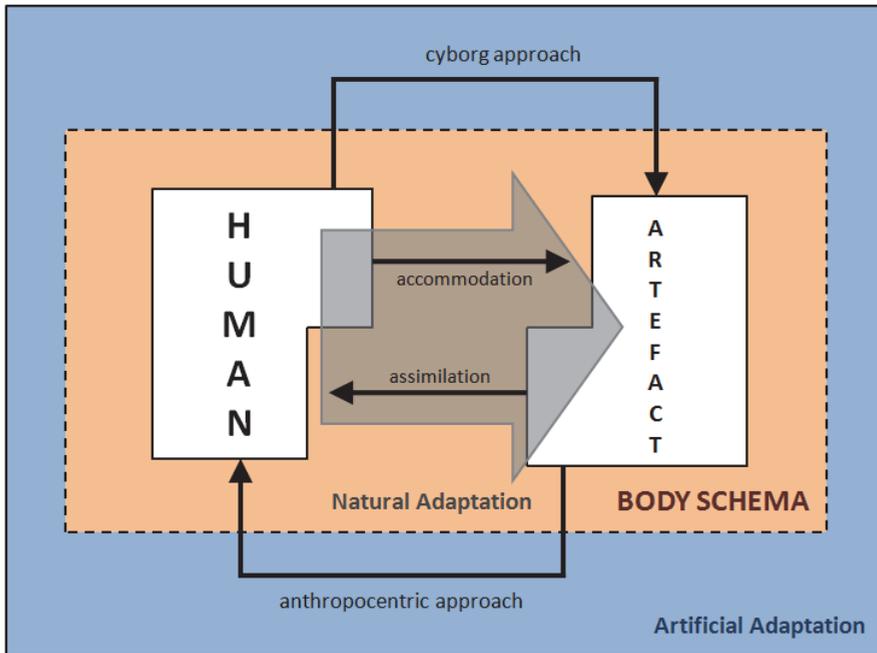
Fig. 1. Principle of the appropriation process that involves an integration of the artefact into the human body schema. To notice that the natural adaptation (accommodation + assimilation) can be boosted by artificial implementations from the artefact to the human being (anthropocentrism) or/and from the human being to the artefact (cyborg).

2. Natural processes

When a living being interacts with the environment, natural processes of adaptation are triggered to enable the individual to fit with her/her surrounding world. Since a long time ago, numerous psychological schools have tried to understand the underlying mechanisms of the human-artefact interaction. Today, some of these theories can be supported by the recent finding in the field of the neuropsychology and neurophysiology. This knowledge has a direct implication to comprehend the user's appropriation of electronic devices. The first part of this chapter will describe the natural human-artefact adaptation process from the point of view of the different scientific areas until its last involvement in the field of information technologies.

2.1 Psychological evidences

2.1.1 Instrumental approach

To understand clearly the concept of a machine appropriation, or more generally an instrument appropriation by a human being, it is necessary to put it back into the original psychological context. The first researcher who attempted to mix psychology and technology was Vygotsky. His approach tried to put activities with instruments as the

central problem of the construction and functioning of cerebral processes of the human being (Vygotsky, 1930). He noted that the integration of an instrument into a behavioural process induces actions linked to its use and to its control. The existence of this mediator between the organism and the surrounding environment transforms the execution of the psychological processes involved in the *instrumental action*. This expression is defined by Vygotsky as a collection of functions that are specifically associated and coordinated following the characteristics of the instrument itself.

Studies by Rabardel, in the context of robotics, extend this approach to the re-composition of the action, following an instrumental approach to human-machine relationships (Rabardel, 1995). An instrument is a hybrid entity that is not reducible to an artefact, which is just the physical component of an instrument. Actually, an instrument emerges from two entities. On one hand, it is composed by the artefact, usually a manufactured product. On the other hand, it is also composed from one or more of its schemes[1] of use, which are the result of the individual construction itself. So overall, the instrument is not only a part of the external world – an artefact – but also a product of the operator's action – the schemes.

However, although artefacts and schemes are associated to define an instrument, they can be relatively independent. Indeed, one scheme can be applied to different artefacts of the same class (e.g., same driving schemes can be used to steering different vehicles) or neighbouring classes (sometimes with possible dramatic consequences, like using heating properties of microwave ovens to dry a pet). On the contrary, one artefact can be associated to different schemes for different functions (e.g., a screwdriver can be used to make a hole).

Consequently, a constant instrument, with qualities of preservation and reuse, consists of a stable association of two variables which, jointly, represent processing and action as a solution to deal with a determinate situation. However, the question is how the construction of this constant instrument begins and happens. Whatever the scheme's side or the artefact's side, this construction does not typically occur ex nihilo. Generally, artefacts are pre-existing, even though they have to be processed by the individual to become instruments. Schemes usually come from the individual repertoire and they are generalized or accommodated to a new artefact. Sometimes, when the artefact design is completely unknown, entirely new schemes have to be constructed. To explain the way in which the construction process of the instrumental entity is carried out, it is necessary to understand the *piagetian* theory of the individual adaptation to her/his surrounding environment.

2.1.2 Adaptation theory

According to Piaget, intelligence is, in the first place, adaptation (Piaget, 1936). The complexity of the living being's organisation is understandable through the balanced relationship that occurs between the individual and the environment. This balance is possible because of the transformations occurring inside the organism, following the characteristics of the environment in which the individual evolves. The aim of these

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[1] The scheme of an action is a structured collection of generalized features of the action, which enables to repeat a same action or to apply this action to new contexts. Thus, a scheme consists of a general template that can reoccur in different circumstances and complete various achievements. For instance, in the case of a prehension task, although we extend more or less an arm or we open more or less a hand according to the object's distance, it is always the same scheme of catching.

modifications is to promote the environment-individual interactions, favourable to the conservation of the living being. Piaget – who analyses the emergence of intelligence according to its sensori-motor aspect – divides adaptation into two complementary processes.

The first one is the assimilation process. According to Piaget, all the external realities, regarding the individual organisation cycle, that respond to an organism's need can be potentially assimilated. This process is defined as a behavioural trend to be preserved. This is possible thanks to the behaviour repetition that becomes schematized, which means that it is supported by one or more schemes. These schemes, composed by a structured collection of generalized features of the action, enable to reproduce a same action and to apply it in new contexts (Piaget & Beth, 1961).

Besides, the schemes represent an active organization of the lived experience, integrating the past. They have a structure with a history and they are transformed following the new experienced situations. So, the story of a scheme is that of its generalization but also its differentiation from the contents it is applied to. The generalization is conceptualized by the assimilation process. In concrete terms, because of an apparent proximity, the use of new objects can be assimilated by pre-existing schemes. On the other hand, the differentiation property is linked to the second process implicated in adaptation: the accommodation process.

When the external realities do not allow a direct assimilation, mechanisms of accommodation are triggered at the scheme level. The example of a stick manipulation learning by the child (Piaget, 1936) helps to understand the complementary nature of the assimilation and accommodation processes. In this experiment, a child is in front of a sofa on which a bottle is placed. The child has a stick with which s/he had learned to hit objects. First, the child tries to catch the bottle directly, which is not possible, and then begins to hit it with the stick. The bottle falls by chance. The child goes on hitting the bottle when it is on the floor. S/he observes the movement of the bottle and begins to push it with the stick to bring it towards her/him. Later, without a stick, s/he uses a book to bring again the bottle towards her/him.

The experiment shows that the child has first used a pre-existing scheme (hit with a stick), but such assimilation does not allow to catch the bottle. The scheme is progressively accommodated, in order to obtain the movement of the object and a new scheme: push with a stick. Then, this last one is generalized to other objects, here a book. Rybarczyk et al. (2002) argue that human-machine interaction follows the same logic. When the machine presents operating modes that are close to those of the operator, they can be directly assimilated. On the contrary, if the device is completely "different", the operator must accommodate her/his schemes to the new device (figure 2). This is this *piagetian* principle of adaptation applied to human-machine relationship which is described here as the mechanism of appropriation[2].

Consequently, in order to achieve a successful ergonomic design, it is essential to take into account the gap existing between the schemes and representations of the operator and the

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[2] This term, which is often employed in the field of educational research to refer to the child's capability of learning to use a pedagogical tool, is not directly used in this sense. Actually, we apply the word following the meaning given by Bullinger (1987), who stresses the appropriation process to the level of sensori-motor integration.

schemes and representations that are necessary to control the machine. Two directions are possible. The first one consists in reducing the gap between the pre-existing schemes of the operator and the schemes that are relevant to control the machine, with the objective of extending the sensori-motor repertoire of the operator. In this case, the operator will try to attribute her/his characteristics to the machine. The second direction is to take into account the existing gap – then ergonomic conception will try to point it out, in order to help the operator to conceptualize it.
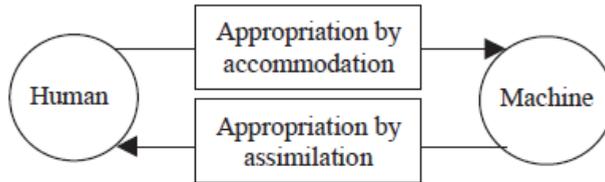

Fig. 2. Application of the adaptation *piagetian* model to human-machine interaction.

2.2 Artefact integration into the body schema

2.2.1 What is body schema?

The precedent section clearly explained that human sensori-motor and cognitive development is achieved primarily through interaction with the surrounding environment. This statement means that each of our interactions with the environment will trigger a sensorial cue, carried out to the central nervous system, to inform this latter about our physical capacities. This mental representation of our functional body, created and updated by the central nervous system, is known as the body schema (Paillard, 1991). More precisely, the body schema is defined as a mental construction or internal model we have about our body and parts of it, with relation to the environment, in movement or in rest. It is built through experience, thanks to the combination of multi-modal sensations. If, indeed, the individual has a more or less conscious representation of his/her body action capabilities, this implies that s/he must have a more or less precise idea of the limits of this body. In others words, if I have the consciousness that my arm has a length of about 70cm, I have the implicit knowledge that my range of action, by simple arm extension, is approximatively an arc of 70cm radius. As motor processes contribute in the first place to the organism construction (O'Regan & Nöe, 2001; Borghi & Cimatti, 2010; Gallese & Sinigaglia, 2010), it suggests a different sensori-motor processing, depending on whether the space considered is reachable vs. unreachable by the hand.

The strongest evidence for distinct representations of near and far space in the human's brain comes from studies of subjects with a well-known neuropsychological disorder called neglect. In a majority of subjects, the lesion involves the right inferior parietal cortex, especially the supramarginal gyrus (Heilman et al., 1983; Husain & Kennard, 1996). In the most common form of neglect, the subject ignores an entire side, or hemifield, of egocentric space, usually the left side (Jeannerod, 1987; Halligan & Marshall, 1994). For example, subjects will incorrectly bisect horizontal lines to the right of the midpoint, thus neglecting the left side of the line. However, recent studies have found that neglect is not a single

monolithic disorder but can be fractionated into a variety of more specific disorders, each of which reflects the involvement of certain components of the brain highly multifaceted architecture for spatial representation (Bisiach, 1997; Vallar, 1998). For the purpose of this paper, the most important type of neglect is sometimes referred to as proximal/distal neglect.

Using exactly the same methods, two different studies described brain-damaged subjects who exhibited opposite types of neglect. The first study, conducted by Halligan and Marshall (1991), concerned a single subject with a large right temporal-parietal lesion. The main experiment consisted in two additional line bisection tasks in the following conditions. First, the subject used an ink pen to bisect horizontal lines at a distance of 45cm, well within arm reach. In a second condition, he used a laser pointer to perform a similar line bisection task at a distance of 244cm, well beyond arm reach. Results show a pointing deviation on the right side in the first condition and a correct pointing in the second condition. This pattern suggests that the subject has a selective impairment of the representation of the near left sector of space. The second study was conducted by Cowey et al. (1994) and employed the same experimental procedures to test other patients with neglect. Contrary to the precedent case, subjects pointed correctly only in the proximal space, which means they had a specific neglect to the far sector.

The fact that these two studies demonstrate opposite performance profiles strongly suggests that the brain contains separate neural systems for representing stimuli in near (or peripersonal) space on the one hand, and in far (or extrapersonal) space on the other side. Neurophysiological studies done with macaque monkeys confirm, from the anatomo-functional point of view, the presence of distinctive neural pathways to process information in each spatial sector. More data are available regarding near space, as compared to far space. Neuro-anatomical substrates dedicated to analyze peripersonal space stretch from the parietal lobe (medial, ventral and anterior intraparietal aeras) to the frontal lobe (premotor areas). These circuits are implicated for reaching, for grasping and for monitoring limb movements in relation to the face. The majority of these neurons has bimodal tactile and visual response properties for a stimulus delivered at a distance inferior to about 100 cm in relation to the skin surface (Graziano & Gross, 1995; Fogassi et al., 1996). This bimodal property delimits the well-know pericorporal (or peripersonal) sector, where the integration of kinaesthetic and visual information will be facilitated, in order to improve the coordination of limb movements with respect to a corporal frame of reference (Rizzolatti et al., 1997; Previc, 1998).

In spite of these evident proofs of differential cerebral treatment, depending on whether action space is proximal or distal, we do not have the consciousness of living in a segmented environment. What could explain the phenomenal continuity of space? A partial answer has been provided by Cowey et al. (1999), investigating whether the boundary between near and far regions of space is abrupt or progressive. To address this question, they asked neglect patients to perform a series of line bisection tasks, at six increasing distances, from 25 to 400cm. Results show an increase in the pointing error at progressively farther distances, suggesting a continuous change from peripersonal to extrapersonal space. In the same way, neurophysiological recordings among animals confirm this overlapping between the two regions of space. So far, it has been shown that neurons in area F4 (pathway of the peripersonal system) have a gradient firing response that is strongest to stimuli within the

proximal region and steadily declines as stimuli are placed farther away (Graziano et al., 1997). The receptive field depth of these neurons also progressively expands as the speed of stimuli towards the body part increases (Fogassi et al., 1996).

2.2.2 Neuroscientific evidences of integration

Such a fuzzy border between spatial sectors suggests, therefore, that spatial layouts are relatively extensible from one to the other. It is, in part, because of this dynamic property that the representation of space around us seems homogenous and coherent, whatever the situation. However, this representational flexibility has certain limitations. Some works trying to delimit more precisely the dynamic properties of the body schema have focused, principally, on the evaluation of the peripersonal space around the hand. To address this question, they have employed, in the majority of case, the experimental paradigm of tool manipulation (Cardinali et al., 2009; Maravita & Iriki, 2004, for a review).

| (a) | (b) |

Fig. 3. Visual receptive fields (vRF) of bimodal neurons for the monkey right arm (yellow area), before (a) and after tool-use (b). Immediately after tool-use the dimension of vRF is enlarged in order to include the length of the rake (adapted from Iriki et al., 1996).

Iriki et al. (1996) have shown, in monkeys, that the activation of far and near space maps can be influenced by the use of tools when the action modifies the spatial relationships between the body and environmental objects (figure 3). They found bimodal neurons in the monkey parietal lobe that coded for the schema of the hand, similar to those studied by Graziano and Gross (1995), and by Fogassi et al. (1996). As already discussed, these neurons fire when a tactile stimulus is delivered to the monkey's hand and when visual objects are presented near the hand tactile receptive field. The most striking feature described by Iriki et al. (1996) was that visual receptive fields of the bimodal neurons could be modified by a purposeful action. Indeed, when the monkeys reached for far objects with a rake, the visual receptive field was enlarged to include the entire length of the rake and to cover the expanded accessible space. The authors explained their results by postulating that, during the reaching movement, the tool was assimilated to the animal's hand, becoming part of the hand representation (Aglioti et al., 1996; Paillard, 1993). The space now reachable by the prolongation of the hand was enlarged, including part of what had previously been far space, and the spatial relationship between the body and objects was modified by the action

of reaching with a tool. As a consequence, far space was remapped as near space and the neurons that fired for near space also fired when what had previously been coded as far space was reached by the rake. Moreover, this extension was reversible, because the elongation of bimodal neurons receptive fields contracted towards the hand after a certain delay after tool use. This constitutes further demonstration of the remapping plasticity of the primate spatial representation.

This modulation of space coding can also be observed in human beings. Berti and Frassinetti (2000) showed in a right brain-damaged patient that, when the cerebral representation of pericorporal space was extended to include a tool used for a purposeful action, the space previously mapped as far was then treated as near, like in monkeys. Patient "PP" had a clear neglect in near space in many different tasks including reading and line bisection. Line bisection in near space was affected by neglect both when the patient had to perform a pointing task with the index finger of the right hand and, when she had to point with a projection light-pen. When the lines were positioned far from the body, neglect was much less severe or even absent when tested using the projection light-pen. This result is very similar to that described by Halligan and Marshall (1991) and, again, shows that the functional space around us can be differently affected by brain damage. However, in Berti and Frassinetti's experiment, the patient was also asked to bisect lines in far space using a stick through which the patient could reach the line. Under this condition, neglect appeared also in far space and was as severe as neglect in near space. This result might be explained in reference to neurophysiological data reported by Iriki et al. (1996). Like in monkeys, the use of a tool extended the body schema, thus enlarging the peripersonal space to include all the space between the patient's body and the stimulus. Far space was, as a consequence, remapped as near. And, because near space representation was affected by neglect, neglect became manifest also in far space.

A similar remapping of distal as proximal space has been demonstrated in patients with cross-modal visuo-tactile extinction (Farnè & Làdavas, 2000). This term refers to a clinic symptom, whereby some patients with right-hemisphere damage fail to report a tactile stimulus delivered to their contralesional left hand when a concurrent visual stimulus is presented to their ipsilesional right hand (Di Pellegrino et al., 1997). This phenomenon can be easily explained by neurophysiological recordings in monkeys, which stress the bimodal characteristic of neurons coding the peripersonal space surrounding each part of the body and especially the hand (Fogassi et al., 1996; Grazziano & Gross, 1995). Indeed, if a similar cell population exists in humans, a visual stimulus near one hand might thereby enhances the representation of that hand (Driver & Spence, 1998), to compete (Driver et al., 1997) with the activity produced by touch on the other hand, thus producing cross-modal extinction when the other hand has been "disadvantaged" by a unilateral lesion (Làdavas et al., 1998).

In Farnè and Làdavas' experiment (2000), cross-modal visuo-tactile extinction was assessed by presenting visual stimuli far from the patient's ipsilesional hand, in correspondence of the distal edge of a rake statically held in their hand. The results show that cross-modal extinction was more severe after the patients used the rake to retrieve distant objects with respect to a condition in which the rake was not used. Again, the evidence of an expansion of peri-hand space lasted for only a few minutes after tool use. Finally, pointing movements towards distant objects also produced cross-modal extinction entirely comparable with that obtained in the pre-tool-use condition, showing that the expansion of hand peripersonal

space is strictly dependent upon the use of the tool, aimed at physically reaching objects located outside the hand reaching space, and it does not merely result from directional motor activity.

2.3 Appropriation of electronic devices

The tool appropriation into the body schema presented above refers to experiments that have been limited to direct interaction with simple tools. In these conditions, perceptivo-motor relationships are relatively straightforward and natural for the human being. So, the question remains whether the user can incorporate an artefact into her/his body schema when the correlation between motor actions and their perceptual consequences is more complex, like in remote control situations.

2.3.1 Virtual reality

The concept of *presence,* defined in the field of virtual reality, resembles the concept of appropriation in certain aspects. The sensation of "being there", in place of the avatar that represents the operator in the virtual world is one example. In Minsky (1980) the term "tele-presence" is used to describe the operator's sensation to be physically present in the space where s/he acts via the machine. Sheridan (1992) proposed to distinguish between virtual presence for virtual reality and "tele-presence" for remote control situations. This separation is not useful in neuroscience (Ijsselsteijn et al., 2000). In fact, the central question is the mental representation of one's human body. Subjects in virtual reality situations say they were mentally more "situated" in the virtual world than in the physical world (Slater & Usoh, 1993). Loomis (1992) distinguishes between the phenomenal body and the physical body to explain the *distal attribution* of an avatar to her/himself in the virtual world. According to this author, in this singular situation, there are three entities. The first one is the objective entity, which is the physical body of the individual. The second is the virtual body, represented by the user body inside the virtual environment (the avatar). The last entity is the body schema or mental representation the user has of her/his own body. When the individual interacts with a mediated world, her/his body schema can be deteriorated by swapping between virtual body and physical body (Meyer & Biocca, 1992). Evidences of *presence* the can be showed following multi-level of analysis, from the phenomenology to the neural activity underlying the embodiment feeling (Ijsselsteijn, 2002).

From the phenomenological point of view, one of the most famous demonstrations of the distal attribution is the rubber hand illusion (Botvinik & Cohen, 1998). In this experiment, a left rubber hand is placed on a table, visible from the participant. On the contrary, the left real hand of the participant is hidden from her/his field of view. When the experimenter synchronously stimulates the subject's hand and the fake hand, by means of two brushes, subject came to feel that the life-size rubber hand was their own. This experiment was reproduced in virtual reality to know whether this phenomenon is replicable in mediated environments (Yuan & Steed, 2010). The participant is placed in a situation of virtual immersion thanks to a head-mounted display. S/he is sat in front a physical table and has to perform various tasks in the virtual environment with her/his right arm. One task is to point at coloured stimuli in a specific order (adaptation of the Simon game) and another one is to drop a ball to a hole. Also, in one condition, an emotional stimulation is induced to the subject, seeing a lamp falling over the virtual hand. The avatar that the participant sees is

displayed from a first person point of view. The presence feeling is gauged through a questionnaire and the galvanic skin response (GSR). The questionnaire results show the participants have the real feeling that the virtual arm is her/his own arm. Furthermore, the increase of the GSR immediately after the falling lamp event is a physiological recording that confirms the self-identification with the avatar. As the magnitude of the response ownership is similar to those demonstrated for the rubber hand illusion, we can deduce that the process of appropriation of a simple artefact would be similar to one occurring with an electronic device.

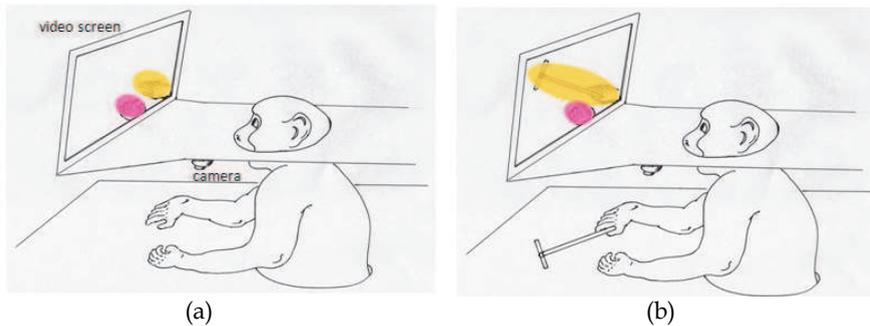(a)   (b)

Fig. 4. Brain parietal lobe processing of primates acting in virtual reality environment. (a) Visual receptive fields (vRF) of each hand are activated around the video recording of the monkey's hand displayed on the screen. (b) Active tool-use extends, along the rake, the vRF of the hand image on the monitor (adapted from Iriki et al., 2001).

For a further exploration of this distal attribution, Iriki et al. (2001) have analysed neurophysiological data of brain monkeys, when the animal is set in remote control situation. Authors carried out an experiment in which monkeys were trained to recognize their own hand on a video monitor. Simultaneously, investigators recorded the activity of bimodal neurons receptive fields localized around the hand (figure 4). First, results showed that visual receptive fields (vRF) were formed around the image of the monkey's hand in the monitor. After tool-use, the vRF around the image of the hand on the monitor extended along the image of the handheld rake, like the vRF extension when viewing the hand directly. In other conditions in the experiment, the size and position of the vRFs of these bimodal neurons were modified accordingly with the expansion, compression or displacement of the hand's image in the video monitor, even though the posture and position (and of course the size) of the real hand remained constant. Furthermore, vRFs for the same neurons were formed around a restricted spot left around the tip of the tool (akin to a computer cursor) when all other images on the monitor were filtered out. These results suggest that the visual image of the hand (and even its "virtual" equivalent, such as a spot of light) in the monitor was treated by the monkeys as an extension of their own body.

2.3.2 Teleoperation

In the neuroscientific studies presented before, tools are relatively simples and the perceptual-motor relationships are quite straightforward for the user. So the question

remains about what the appropriation process is when the human-artefact interaction is highly complex, like in teleoperation of a robotic device. Indeed, in the case of the remote control of an electromechanical machine, in addition to an indirect contact with the artefact, the interface is significantly more refined. The appropriation of a telerobot according to a process of device embodiment into the operator's body schema was studied by Rybarczyk and Mestre (2011). To do that, the authors compared the performance of human beings in a natural condition vs. other in a teleoperated condition, in a discrimination task of the reachable area of an effector (participant's arm vs. telerobotic arm). The study is presented in this section.

Method

The originality of this experiment is thus to reveal the body schema's alteration, not through the study of neuropsychological cases, but using behavioural assessment in normal subjects placed in a teleoperation situation. This assessment is based on the concept of affordance, describing the interaction relationships between an actor (or an effector) and the surrounding environment. The affordance of an object or situation is related to the activities that it offers or "affords" for an organism possessing given action capabilities (Gibson, 1979; Turvey & Shaw, 1979). Such functional possibilities for action are determined by the fit between properties of the environment and properties of the organism. For example, an object "affords" grasping if its size, shape and surface texture are compatible with the functional morphology of the organism's prehensile limb (Newell & Scully, 1987). In a similar way, an object at distance affords a simple extension movement (to touch it) if its length is smaller than the human's arm dimension.

Warren and Whang (1987) have proposed a measurement method to describe the attunement of environmental variables to organism's action variables. They defined the "Pi" dimensionless numbers, being a ratio between an environmental dimension and a body dimension. As the ratio is varied, optimal points in the ecosystem may emerge for preferred states at which a given action is most comfortable or efficient, and critical points will emerge, at which the limits on an action are reached and a phase transition to a qualitatively different action occurs. Warren (1984) studied the case of stair climbing, showing that there is a particular ratio between the stairs height and leg length for which ascending a stair is optimally comfortable and efficient (in energetical terms). In the following experimental conditions, the object to catch is at a variable distance (D) in relation to the robotics' arm length (R). Thus, as distance increases, appears a critical distance for which the grasping by simple extension becomes impossible, and requires the transition to a prehensile action that would be coupled, for example, with a locomotion movement of the mobile arm's mounted platform. The value of this critical distance is given by the Pi ratio ($\Pi = D/R$) becoming superior to 1.

If we ask an operator to estimate the maximum reachable distance, the value of the Pi ratio will inform us about the operator's representation of space, caused by his interaction with the machine. Indeed, to estimate the distance in which an extension of the arm is not enough to catch an object, the operator needs to carry out a translation from absolute coordinates of the environment into robotics' system coordinates (Fitch & Turvey, 1978). The Pi ratio thus delivers a numerical estimation of the operator's body schema, on which statistical analysis can be conducted. Pi ratio is thus defined as the subject's estimation of the maximal distance of grasping divided by the arm's length. Thus, the more the ratio is close to 1, the more the

individual has a good representation of his range of action in space and therefore the more his/her body schema conforms to actual action capabilities. Afterwards, in robotic conditions, the Pi ratio obtained when the subject is using the manipulator is compared with that obtained in natural conditions (with the subject's own arm). If the Pi ratio calculated for the peribrachial space is not statistically different between the two conditions, this result might be interpreted in terms of an extension of the operator's pericorporal space to the remote manipulator arm length.

Procedure

During the experiment, the robot or the human being, depending on the condition, was placed in front of a table (figure 5a). The rotation axis of the subject's or robotic shoulder was aligned along the median axis of the table. From the centre of this axis radiated five rays, visible only for the experimenter. These straight lines were 20 degrees apart. They stretched out with respect to the median line, which was the 0° ray, on an angular sector, from -40 to 40 degrees (figure 5b). In the teleoperated condition, the camera position was located up, on the left and slightly behind (to compensate for the limitation of camera optical field of view) in relation to the rotation axis (or shoulder) of the robot. In the "natural" condition, individuals were put exactly in the same location, relatively to the experimental device, than the robot. This means that their right shoulder was centered on a position identical to that of the robot arm's rotation axis.
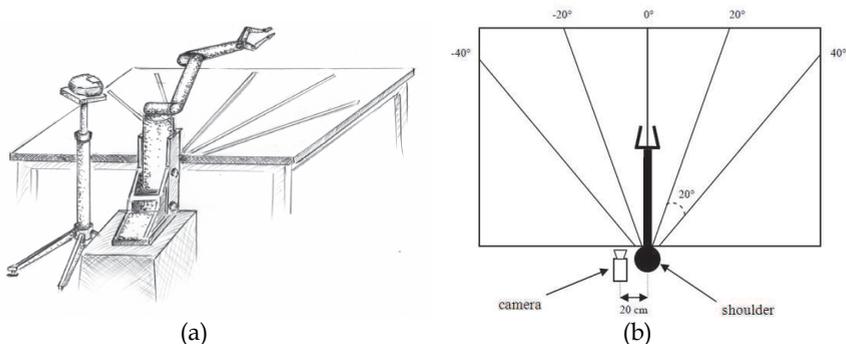

(a)   (b)

Fig. 5. (a) Schematic representation of the experimental device (robotic condition only), in ¾ right back view. (b) Details of the experimental configuration characteristics, in top view.

The experimental procedure followed three successive steps. In a first step, each subject had to grasp a cylindrical object, 2.5cm in diameter and 8cm high, by extending their right arm or with the robotics' arm, depending on the condition. This grasping was carried out for each ray, for four random positions close (inferior and superior) to the maximal length of arm's extension. So, subjects were always confronted with reachable and unreachable objects in all rays. Whatever the case, subjects were ordered to try to catch the cylinder the more rapidly and precisely possible by a simple arm's extension, that is to say without coupling it with a chest's movement. Indeed, during all the experiment, the subject's back was kept in close contact with the back of the chair. Finally, the starting point of each movement was always the same, the pair of pliers or hand's main axis aligned with the ray where the grasping occurred.

After this motor stage came a calibration stage. Here, subject must put the object, held between the thumb and the index finger or the pair of pliers end, the farthest possible along each ray, by a movement of simple arm's extension. Thus, the distance obtained for each ray gives us the reference value (R) of the range of action or peripersonal space of human's arm and robotics' arm. This value is used as denominator to calculate the Pi ratio.

The last stage was designed to estimate the threshold distance for which one subject estimated a transition between his grasping space and his locomotion space. To do that, eight object positions have been chosen according to the reference length value (R) obtained in the calibration stage. Precisely, these eight positions were symmetrically distributed on both sides of the reference length so as to have four supraliminal and four infraliminal values. Thus, these positions had a value of ±1cm, ±4cm, ±8cm and ±13cm in relation to the reference (R). Subject's task was to answer by "yes" or "no" to the question: "Do you think you could catch the object presented with a simple arm's extension?". To obtain a precise threshold value, each eight positions were presented ten times for each five rays. The presentation order of object positions and rays tested has been randomised in each condition. Then, the 80 answers have been counted to obtain the threshold (S), which is the distance value in respect of a same percentage of answers "yes" and "no", equal to 50% (Bonnet, 1986).

Results

As shown on the figure 6, Pi in the robotic condition is not statistically different from Pi in the natural condition (F[1, 6] = 2.48; NS). This result suggests that, in a remote control situation, the capacity of the human being to delimit his grasping space is the same whatever the effector's organ is his own arm or a teleoperated robotics' arm. Furthermore, this similarity happens rapidly, since no effect of interaction between conditions and experimental sessions is recorded (F[3, 36] = 0.48; NS). These data mean that a human operator, acting on the environment through a robotics' telemanipulator tool, can circumscribe her/his range of action almost as precisely as when s/he performs the action with her/his own arm. Also, because of this remapping occurs after limited training, humans appear to rapidly perceive the affordance of the remote control arm. So overall, the study suggests that a teleoperated device can rapidly be appropriated and incorporated into the operator's body schema, in the same way that was demonstrated for more simple tools (Maravita et al., 2001; Carlson et al., 2010).
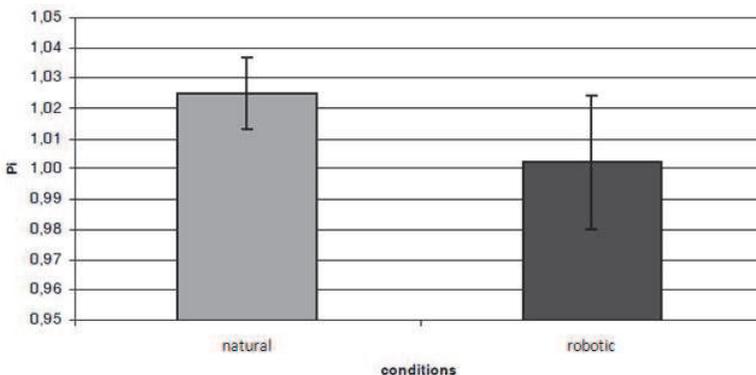

Fig. 6. Pi index values of grasping distance evaluation for each experimental condition.

3. Artificial processes

Beyond the obvious natural processes of appropriation described earlier, the "matching" between the human operator and the electromechanical machine can also be achieved through artificial processes. As the natural adaptation occurs in both directions, the artificial adaptation can also be implemented according to two approaches. The first approach, called anthropocentric, is applied from the machine to the human. The objective is to bring closer the way in which the machine works to the human skills and, consequently, promote an adaptation mainly through an assimilation process. The other approach is carried out in the opposite direction. In this case, the human-machine interaction is improved via an implementation of electro-computational components in the biological organism. Because the living being gets some machine-like capacities, this new generation of individuals is called cyborg - the contraction between cybernetic and organism. This section explains these two complementary approaches through examples coming from neurorobotics studies.

3.1 Anthropocentric approach

Human operators tend to attribute properties of themselves to a used tool, at least in an initial stage (Laborde & Mejias, 1985; Mendelsohn, 1986). So, artefact movements are translated by the user in terms of her/his own motricity. Moreover, Mendelsohn (1986) noticed that the construction of an anthropocentric representation of the machine is enhanced by the similarity between the machine's characteristics and the operator's schemes. This similarity ensures that the individual makes an easier first contact with the system. When this projection is relevant, it involves an assimilation process in the cognition and action schemes of the user. For instance, the control interface of the telemanipulator presented by Gaillard (1993) facilitates such assimilation. In this device, the Cartesian coordinate system of the robot is isomorphic to the corporal coordinate system of the operator. Therefore, the device can be qualified as egocentric. The operator can make a projection of her/his body schema into the working space of the robot. The readjustments are few and the learning process is improved because the system's design preserves the natural movement direction. In such configuration, the human operator is rapidly able to apply an efficient internal control and planning of the movement, thanks to the spatio-temporal isomorphism between the human and the machine. In order to demonstrate the advantages of the anthropocentric approach, two experiments of implementation of human-like properties in the machine are presented below, being one from a morphological point of view and the other from a functional point of view.

3.1.1 Morphological aspect

In the section 2.3.2, signs of appropriation appear when the topological relationship between the camera and the robotic arms is designed according to an anthropomorphic architecture (camera located up and on the left in relation to the robot shoulder, in order to mimic a right arm). So, another point studied by Rybarczyk and Mestre (2011) was to test the effects of the anthropomorphism reduction on the appropriation process. This experiment is described next.

Experimental design

The same experimental configuration, procedure and evaluation factor ("Pi") as described in section 2.3.2 are used in this study. The only differences in relation to the previous

description are the kind and number of conditions and data analysed. Here, three teleoperation conditions were tested. In the three conditions the robotic arm's position never changed, it was only the camera locations in relation to it which changed (figure 7). The camera locations were at equidistance with respect to the centre of table. So, they were arranged along a virtual circle of radius equal to the half length of the table. Consequently, it was only the angular position on the circle which distinguished one teleoperation condition from the other.
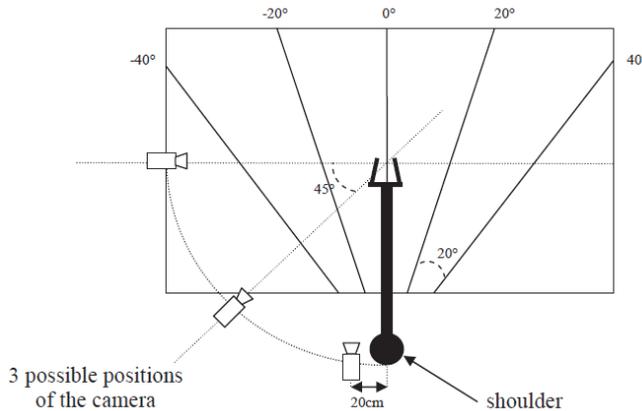
Fig. 7. Three camera position conditions tested in the experiment.

The first camera position was positioned up and on the left in relation to the robot shoulder. Such configuration was defined as "anthropomorphic", because it respects the topological relationship between the cephalic organ and the right superior limb of the human being. So, this design will be called more specifically "right anthropomorphic". In the second condition, known as "bias" condition, the camera was placed at a bigger eccentricity angle, compared to the first one. This angle was equal to 45° in relation to the 0° ray. Finally, the last camera was positioned perpendicularly in comparison with the antero-posterior arm's axis, which broke all morphological identity with the human model. This last configuration was called "side" condition.

In terms of data, three other factors (in addition to "Pi") were analysed. First, the execution time was recorded in each experimental condition. Second, another index of the movement quality has been calculated from this motor task. It was called "spatial error". It was defined as the ratio of the movement length of the robotics' pliers, carried out by the operator, on the shorter distance between the starting point and the arrival point of the movement. Finally, this movement length has been used to calculate a second "Pi" value, called "Pi2", which is the ratio of the estimated distance of catching (D) on the movement length executed by the subject, and not the robotics' arm length (R), as in the Pi index.

Results

Figure 8a shows a general tendency for a greater velocity in the execution time of the movement in an anthropomorphic condition, even if this superiority is only significant with

regard to the side condition (F [1, 6] = 6.1; p < 0.05). On the figure 8b, we can observe the same tendency of the anthropomorphic condition to produce less spatial error than the others conditions. Precisely, the anthropomorphic condition ensures a more direct movement from the starting to the arrival point than in the side condition (F [1, 6] = 6.05; p < 0.05), but this difference is not significant in comparison with the bias configuration (F [1, 6] = 3.14; NS). It means that the sensori-motor effort to carry out the catching task has linearly increased as the camera eccentricy was increased.

(a)   (b)
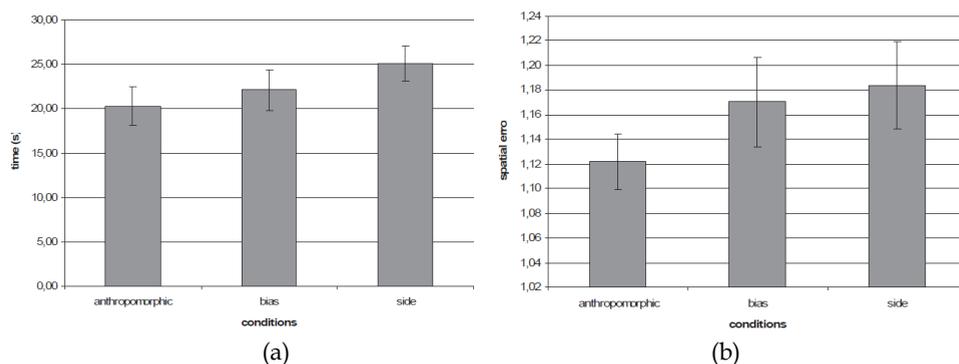
Fig. 8. (a) Average times of the execution of the movement following the three relative positions of the camera with respect to the arm. (b) Spatial error according to the three teleoperated conditions.

From the point of view of the perception task, as shown in figure 9a, "Pi" values of grasping distance evaluation by arm's extension are not the same depending on the teleoperated condition (F [2, 9] = 9.05; p < 0.007). We notice an elevation of the "Pi" from the 1 reference value (and the "Pi" obtained in "natural" condition) the more the teleoperated condition moves away from the anthropomorphic configuration, with a significant difference between natural and side condition (F [1, 6] = 16.8; p < 0.006). "Pi2" analysis may explains such increment in "Pi". Indeed, when the estimated distance of catching is divided by the distance carried out by the operator in the motor stage, the Pi value of the side condition is close to 1 (figure 9b). Moreover, this second Pi index decreases linearly toward the anthropomorphic configuration. This observation suggests a strong influence of sensorimotor efforts on the catching distance estimation, the more the teleoperated condition moves away from an anthropomorphic configuration.

The fundamental result of this experiment is to stress that the body schema extension has certain limitations, in particular when the visual organ/effector organ topological relationship is too much distorted to lead to a perception of "distal attribution" (Loomis, 1992). Such is the case in the side condition, in which results show that the operator cannot have a correct representation of the robotics' arm capacities. The more the operator's vision is shifted forward and to the side (with respect to the effector's axis), the more s/he overestimates the maximal grasping distance. The overestimation can be explained by a motor account, since the motor effort seems to increase too. Besides, it has been demonstrated that perceived distances increase with an augmentation of motor activity and difficulty (Proffit et al., 2003; Witt et al., 2004). These fundamental differences between the

anthropomorphic levels of each condition suggest that the appropriation process occurs, at least in teleoperated situation, only under restricted conditions. The study shows that static morphological features can interact on the dynamic mental construction of the body schema. These results are supported by works demonstrating that the rubber hand illusion can be elicited even if the effector has no visual resemblance to a human hand (Armel & Ramachandran, 2003) – which is the case of the robotic manipulator – but does not happen if the shift between the visual referential of the individual and the effector organ exceeds the peripersonal area (Lloyd, 2007).
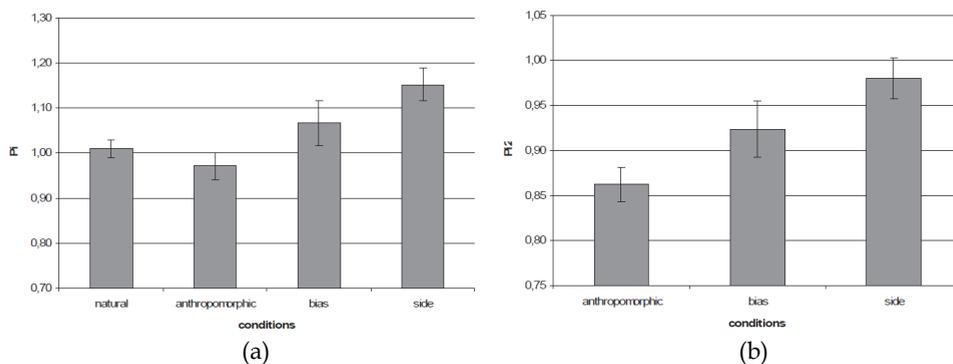

Fig. 9. (a) Pi index values of grasping distance evaluation following each experimental condition (the natural value is added from the previous study). (b) Pi2 index values of grasping distance evaluation for each condition. On the contrary of the previous Pi, in this case the estimated distance is divided by the distance carried out by the arm in the first motor task of the experiment.

3.1.2 Functional aspect

The anthropocentric approach can be applied not only on the morphological design, but also on the functional architecture of the system. To complete this approach in the field of teleoperation, Rybarczyk et al. (2004) researched whether the implementation of a human-like behaviour in the way in which the telerobot works could improve the HMI. In this experiment – summarised below – visuo-motor mechanicals of anticipation inspired from the living beings were implemented in a mobile platform, in order to improve the steering control.

Modelling of the human behaviour

Teleoperation is a situation characterized by the deterioration or absence of many sensorimotor contingencies, in comparison with natural conditions. However, one sensorial modality that is still present, and thus overexploited, is vision (Terré, 1990). One consequence is that any degradation of visual information and feedback will have serious consequences for the quality of robot control. Conversely, the control of the machine displacement can be strongly improved by the "quality" of visual information. In teleoperation, the visual limitations are mainly related to the important reduction of the visual field size and to the transmission delay of images (Massimo & Sheridan, 1989). In fact,

these constraints are associated with spatio-temporal characteristics of human visual perception. One strategy that has developed during evolution to cope with limited bandwidth problems is visuo-motor anticipation. This strategy consists in directing the gaze to a place in space, which is a goal or sub-goal of displacement, before actually moving the body in that direction. For example, during the control of locomotion around corners, the subject does not preserve his/her gaze axis rigorously aligned with the rest of the body, but directs this one towards the inside of the trajectory (Grasso et al., 1996). Thus, gaze orientation would anticipate displacement orientation, by systematically anticipating the changes in the direction of locomotion by a temporal interval of about one second. A control strategy following an organization of the type "I go where I look" seems to underlie the guidance of locomotion (Land, 1998). The same thing occurs for the bypassing of a reference mark. The gaze and body movements' recordings show that the gaze is directed to the reference mark before the individual reaches its level, the realignment of the head in the direction of walk being carried out only after its crossing (Grasso et al., 1998). This suggests that gaze orientation is controlled step by step according to a predictive mechanism of the new direction to follow.
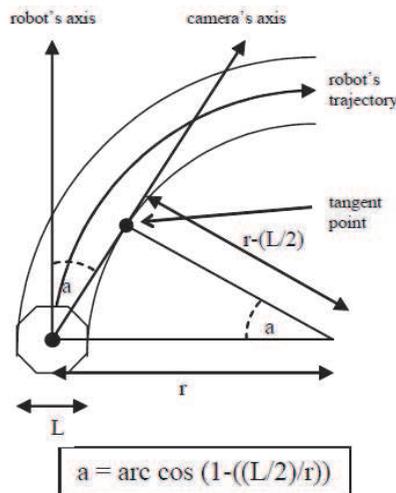

Fig. 10. Implementation of visuo-motor anticipation according to a non-human-like model. The camera's rotation angle is computed by the curve radius (r) of the robot's trajectory, using trigonometric laws. Here, cos a=(r(L/2))/r, where the semi-width of the robot equals L/2. The radius (r) is obtained by dividing the translation velocity by the rotation velocity of the robot.

Such observations were also collected in the case of automobile control. Under these conditions, the driver's gaze axis is directed to the tangent point of the curve one to two seconds before reaching the convexity of the curve (Land & Lee, 1994). By this strategy the driver seeks to use the particular optical properties of the tangent to the turn, in order to guide the trajectory. The tangent point corresponds to a singularity in the optic flow field, being motionless when the driver's trajectory is aligned with the road's curvature.

Psychophysical studies show that this gazing strategy corresponds to an optimization of information pick-up for the control of the trajectory (Mestre, 2001). As a consequence, it seems that this visual anticipation behaviour is useful for trajectory control. Rybarczyk et al. (2004) implemented this type of behaviour on a teleoperated mobile robot, in order to test whether this could help human-machine cooperation. To do that, an analogy was made between the human gaze during locomotion control and the mobile camera on the mobile robot. The figure 10 describes the camera-robot coupling that simulates the human-like visuo-motor anticipation. The expected result was a facilitation of the navigation control of the robot, following the example of human locomotion supported by predictive properties of the brain.

Experimental design

The telerobotic system was composed of two principal elements: a mobile platform and a control station. The robotic platform was equipped with a mobile camera. The robot was moved by two independent driving wheels, a free wheel in front of the vehicle allowing its stability. The engines were of the same type as those which equip electric wheelchairs. The optical camera field of view was 50° in the horizontal and 38° in the vertical dimension. This sensor "sent" to the operator an image of the environment in which the robot evolved, on a terminal display having a height of 23 cm and a width of 31 cm. The whole system, engines and sensors, was controlled by a PC embarked on the robot. This PC was connected to the computer of the control station through a TCP/IP HF connection. Client/server software architecture structured the informatics part. The control interface was using the PC keyboard, by which the operator controlled the direction and displacement velocity of the platform.

The first situation was a "non-human" condition, in which there was no anticipation, since the camera was motionless, aligned with the orientation of the robot. In the second condition, called "human-like", the camera orientation anticipated the platform displacement. In the two cases, the subjects were placed in a teleoperated situation, i.e. they only had an indirect vision of the experimental environment. The task of the subjects consisted in making the robot a slalom course between four boundary marks. The instruction given to them was to carry out the course as soon as fast as possible without colliding with the boundary marks. The analysis of the results was carried out on three parameters: the path execution time and the collision number and the trajectories smoothness.

This last parameter brings deep behavioural information, since it is not only based on a pure performance (as the first two parameters) but on the motor skills the task is completed. To calculate the smoothness of trajectories, an index was computed on the basis of the frequency distribution of the instantaneous curve radius of each trajectory (Péruch & Mestre, 1999). The following formula was used:

$$r(m) = \frac{v(m/sec)}{w(radians/sec)},$$

where r corresponds to the curve radius, v is the instantaneous speed, and w is the absolute instantaneous rotation speed. Then, the curve radius is converted in decimal logarithm. If the vehicle nearly stops and makes a single rotation, the curve radius is very small (< 1), and

the logarithmic value of r is negative. If the vehicle makes a combination of translation and rotation, the curve radius is ≥ 1 and its logarithm is ≥ 0. If before each curve the participant stops and makes a single rotation, the distribution of curve radii will be bimodal, with one spike centered on negative values of the logarithm and the other spike centered on positive values. If the participant makes a smooth (or curvilinear) trajectory, the distribution will rather be unimodal and centered on a value ≥ 0 of the logarithm of the curve radius. For each trajectory, the distribution of the logarithm of the curve radii was computed and distributed in categories from -4 to +3. The distributions were normalized, the occurrences of curve radii in each category being expressed as a percentage of the total number of occurrences for each trajectory.

Results

The figure 11a shows that the average time for the execution time of the travel is significantly lower when the camera anticipates (human-like) over the platform displacement in comparison with the motionless camera (non-human) (F [1, 12] = 7.58; p < 0.02). Also, data displayed on the figure 11b show that the same significant effect in favour of the mobile camera is obtained for the number of collisions (F [1, 12] = 5.52; p < 0.04).
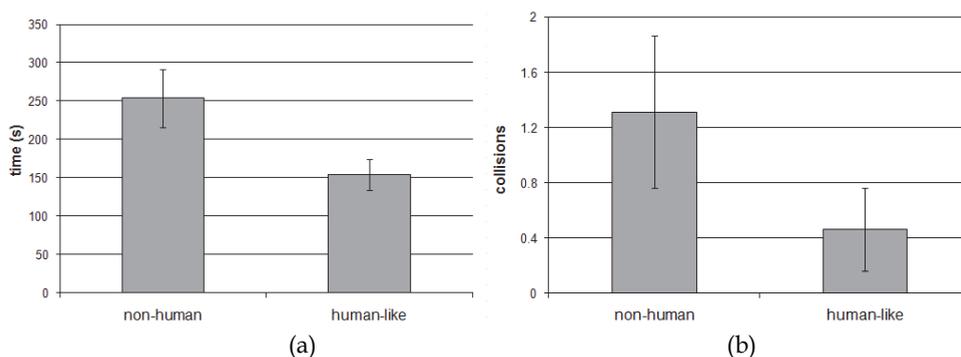

Fig. 11. (a) Mean time of execution. (b) Mean number of collisions.

Also, the trajectory smoothness is different following the conditions. When the camera anticipates over the robot's displacement, the path is more curvilinear than when this human-like behaviour is not implemented on the mobile platform (figure 12). ANOVA test confirms a statistically higher percentage of occurrences of curvilinear trajectories (higher peak) for the anticipating camera in comparison with the motionless camera condition (F [1, 12] = 69.31; p < 0.00001). In addition, curves negotiated with stops (smaller peak) are significantly fewer in human-like condition than non-human condition (F [1, 12] = 19.90; p < 0.0008). These data tend to show that the steering control is more natural when the visuo-motor anticipation is implemented in the remote mobile device. So overall, these results demonstrate a better HMI when the machine exhibits human-like behaviours in the way in which the system works. Beyond the pure performance improvement, the anthropocentric approach seems to make easier and intuitive the human control over the machine, by promoting a human-machine cooperation through an appropriation process by assimilation dominance.
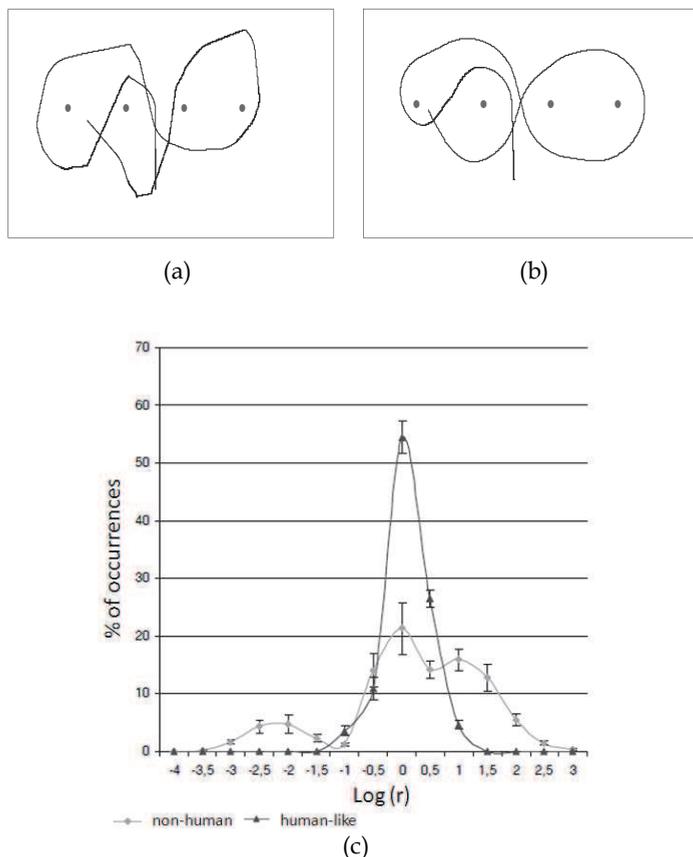
(a)   (b)

(c)

Fig. 12. Trajectories in fixed camera mode – non-human – (a) and anticipating camera mode – human-like – (b). Average distribution of (logarithms of) curve radius, expressed as a percentage of the total number of occurrences, following the two experimental conditions of vision (c).

3.2 Cyborg approach

Another way to reduce the gap between the human and the machine is to implement an approach in the direction opposite to the previous one, which means from the human to the machine. In other words, the idea of the cyber approach is to bring some human functions closer to the way in which the machine works. This paradigm of the HMI has first been applied in assistive technologies (Hochberg et al., 2006). Most motor handicapped people are really dependent on electromechanical artefacts in order to carry on a "normal" life. However, many of them have lost capabilities in using lower or upper members. Consequently, traditional Human-Machine Interfaces are useless for them. With the cyborg paradigm and the numerous possible implementations, such as Brain-Computer Interface (BCI), severely disabled people may compensate a capability loss with a tight linkage between the machine and their nervous system. Indeed, the idea of a cyborg implementation

is to directly connect the human nervous system to the control system of an electronic device. Therefore, a simple nervous impulse would be enough to interact with the machine.

Besides bringing back functionalities to a brainstem stroke victim, a cyborg has many other advantages over a usual interface. Since the motor command is directly measured from the nerve, it avoids a noisy signal and enables a better discrimination of the human intention. Moreover, the close human-machine relationship may be achieved not only for the motor control but also for the sensorial feed-back. If electrodes are implanted on sensorial fibres, a signal collected from electromechanical sensors of the machine can provide the user the sensations similar to those of a stimulation of her/his own biological sensor. An application for sensate prosthesis has already been investigated (Warwick, 2009). An adaptation to superficial electrodes could be imagined for sensate robotic arms, which would allow the operator to employ lower level reflexes that exist within the central nervous system, making control of the robot more subconscious.

The simplification of the control interface and, subsequently, the mental workload diminution, are a key idea brought by the cyborgs. It is common that a mediated action, carried out through a robot, for instance, implies a complex combination of motor movement which can be completely different in comparison to the same action performed in natural conditions, because of the interface. However, if the input and output are correctly connected between the human and the machine, the emitted brain signal to control the device will be the same as to control the human body itself, with the obvious advantages in terms of HMI. At last, the introduction of an electronic device inside the biological organism may enhance the human properties too, as it was demonstrated by an experiment carried out by Warwick et al. (2005) in which an extra sensory input (signals from ultrasonic sensors) is directly transmitted to the nervous system, allowing this information to be recognised and used by the individual. The acquisition of these extra abilities implies the human to make a high effort of adaptation to a device that brings a completely new source of information. In this case, the appropriation process will be essentially supported by an accommodation of pre-existing schemes and a possible creation of new ones.

4. Conclusion

The tool appropriation occurs when the artefact is completely integrated into the human sensori-motor loop (or schemes) in order to become transparent, which means it disappears from the field of consciousness. From a psychological point of view, the appropriation involves two complementary processes – accommodation and assimilation – in which the gap between the operator and the way in which the machine works is reduced. During this adaptation, the tool is progressively integrated into the operator's body schema, which is not only a phenomenological but also a neurological transformation of the individual. A better knowledge of this phenomenon is crucial to improve the HMI. Indeed, anthropocentric implementations can boost the human-machine cooperation through an appropriation process mainly based on assimilation mechanisms. On the other hand, a cyborg approach may enhance the human abilities by stimulating schemes' accommodation.

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Human Machine Interaction - Getting Closer

Edited by Mr Inaki Maurtua

In this book, the reader will find a set of papers divided into two sections. The first section presents different proposals focused on the human-machine interaction development process. The second section is devoted to different aspects of interaction, with a special emphasis on the physical interaction.

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