Human-like conception of a remote control robotic system

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Abstract – In remote control situations, sensorial impoverishment is one of the main difficulties. One way to minimize its influence on the system's performance is helping the human operator to perceive and understand the remote system's behavior. This paper is based on the concept of *appropriation* of an object by a user, derived from Piaget's theory of *adaptation*. This developmental psychologist proposed that humans adapt themselves to the external world through two complementary processes: *Assimilation* corresponds to the generalization of pre-existing schemes to the use of a new device or object. *Accommodation* corresponds to the differentiation of pre-existing schemes, which leads to the development of new schemes. This theoretical framework was tentatively applied to the remote control of a manipulator arm. Experiments were conducted on this device, in order to test whether the anthropomorphic aspects of the remote systems could help the operator to adapt to the device. The outcome of this successful adaptation process would then lead to an appropriation by the operator of the remote device characteristics.

Keywords: Remote control, appropriation, robotics.

I. INTRODUCTION

The most important problem in remote control tasks arises from sensorial impoverishment due to the separation between the entity that controls the action (the operator) and the entity that executes the operator's commands (the machine). The most common adapted solution to solve this problem is to try to optimize man-machine co-operation. Key concept is task allocation ([HOC00]) between man and machine. One initial idea was to compare, for a given task, the performance of man and machine, and to assign it to the agent with the best result. However, several criticisms have been formulated. The main one is that, while some tasks are totally executed by the machine, the human operator still keeps responsibility for the global system. In some cases, this strategy results in the abandon of automatic modes by the operator ([VAN94]). The notion of joint cognitive systems, introduced in [HOL83] and further developed ([RAS94], [WOO95]), suggests that "the system must facilitate the appropriation of the system response by the operator" ([KAR95]). So, the problem is not only that of task allocation but that of how the operator understands and masters the system's overall behavior.

In this context, the present paper deals with the concept of appropriation, extrapolated from Piaget's theory of adaptation of a subject to the external world (section II). In section III, the impact of human-like conception of a remote system on the human capacity to control it is studied. Section IV gives experimental results obtained with a real manipulator arm.

II. APPROPRIATION

Remote control situations are related to the question of appropriation of a tool, distant in this case, by the operator. The first researcher who tried to mix psychology and technology is Vygotsky ([VYG30]). He noted that the integration of an instrument into a behavioral process induces actions linked to its use and to its control. Studies by Rabardel in the context of robotics extend this approach to the re-composition of the action, following an instrumental approach to man-machine relationships ([RAB91]). An instrument is not only a part of the external world (artifact) but also a product of the action of the operator (scheme). However, although artifacts and schemes are associated to define an instrument, they can be relatively independent. Indeed, one scheme can be applied to different artifacts of the same class (driving schemes for different cars) or neighboring classes (sometimes with possible dramatic consequences, for example using heating properties of microwave ovens to dry a pet). On the contrary, one artifact can be associated to different schemes for different functions (a screw driver can be used to make a hole). Finally, an instrument is a stable association of an artifact and different identified schemes. Generally, artifacts exist. Schemes appear by a process of generalization of pre-existing schemes or by the construction of totally new schemes.

To understand the origin of instrument construction, it is necessary to study the concept of adaptation introduced by Piaget. According to [PIA36] (translated into English in 1952 [PIA52]), intelligence is first of all a matter of adaptation. Two complementary processes are involved. The first one is assimilation, which consists in the generalization of pre-existing schemes. Because of an apparent proximity or a situation proximity, the use of new objects can be assimilated to pre-existing schemes. The second adaptation process (accommodation) consists in the differentiation of pre-existing schemes.

We suggest 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 his/her schemes to the new device. Consequently, taking into account the gap between existing schemes and representations of the operator and the schemes and representations that are necessary to control the robot is essential to achieve a successful ergonomic conception. 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 his/her characteristics to the machine. The second direction is to take the gap into account. In the present study, we tried to explore the first direction. Our system potentially presents physical characteristics (anthropomorphic arm, Cartesian control and video feedback) that were supposed to fit the operator's pre-existing frames of reference.

III. HUMAN-LIKE CONCEPTION

This paper deals with a tentative human-like conception of a robotic device, aiming at making distant scene interpretation and distant action perception easier for the operator. IBISC (Informatique, Biologie Intégrative et Systèmes Complexes) develops the ARPH (French acronym for Robotic Assistance to Person with Handicap) project since 1994. The objective is to give a degree of autonomy to disabled people in daily life. A manipulator arm is embarked on-board a mobile base to restore, at least partially, the manipulative function. Ultrasonic sensors are used for the safe displacement of the mobile base. A camera, on-board the base, delivers visual information to the user. The system is more precisely described in [HOP02].

Two aspects are taken into account. The morpho-functional aspect is developed for mobility (remote control of the mobile base trajectory), by implementation of visuo-motor anticipation mechanisms. It has been described in [MES05]. The morphological aspect is used for optimization of the manipulation function, by positioning the visual reference frame with reference to the grasping device. This second aspect is the purpose of this paper.

The objective of this work is to study if an anthropomorphic "camera-arm" configuration on the remote controlled robot facilitates the control of the system. We assume that making appropriation easier for the operator is one interesting way to reach our goal. The idea is to permit the operator to adapt to the remote system principally by assimilation. The best way to measure the level of assimilation is to determine if the operator has transposed her/his corporal representation in space on the remote system. Section A introduces human space representation from different points of view: psychological, neuro-psychological and neuro-physiological. Section B presents criteria used to evaluate if the operator has transposed her/his corporal scheme onto the remote system (assimilation) or not (accommodation).

A. Space representation

Space functional organization has been studied from different points of view. From a psychophysical point of view, three concentric spaces are considered around the operator. Personal space corresponds to the spatial range in which objects can be manipulated by arm extension. Action space, about 30 meters, corresponds to a kind of relational space, in which it is possible to communicate, to move quickly from one point to another or to exchange objects. Beyond 30 meters, in the view space, movements are less easy to detect. Different sources of information are used to detect space according to distance ([CUT97]). From a neuro-psychological point of view, near space and far space are distinguished. Some pathologies have been described, in which patients differentially lack mental representations for either near or far space ([COW99]). From a neuro-physiological point of view, studies have shown that different cerebral areas are activated, depending on whether peri-corporal or extra-corporal space is involved in the control of action ([JEA97]).

This dichotomy in two or three spaces has no precise limit. Body schema can be defined as a system of preconscious, sub-personal processes that play a dynamic role in governing posture and movement [HEA20]. It results from dynamic properties. [IRI96] shows that when a monkey uses a tool, its peri-corporal space extends to the accessible space using this tool. In the case of peri-personal neglect, peri-corporal space is extended by the stick dimension ([BER00]). In a remote control situation, the intervention field of the operator increases in proportion with the mechanical tool. Following this, it might be possible to make the hypothesis that the same peri-corporal space extension of the operator will include the remote controlled robot. But another characteristic of a remote control situation is that no physical contact with the tool exists. That specificity might disrupt the visuo-tactile integration process. Indeed, previous studies have shown that there is no peri-manual space extension in the case of physical discontinuity between the operator and a stick when the relation is passive ([MAR01]). In our case, the operator is active but has no tactile feedback. It is also important to point out that perception-action relationships are more difficult in remote control situation than when the operator manipulates a simple tool. Specific sensori-motor distortions appear with 2D screen for 3D initial information ([PEN02], [PEN03]). Consequently, the very particular context of remote control operation requires a specific study of space representation modulations. In particular, it is useful to study perception only conditions (IV.B) and perception-action conditions (IV.C).

B. Evaluation criteria

To evaluate appropriation of the robotic system, [WAR87] defines a dimensionless number Π to characterize the ratio between a dimension of the human organism and an experimental environmental variable associated to it. It is then possible to identify optimal ratios, for which actions will be easier or efficient and, in the opposite, critical ratios for which actions will be more difficult to carry out. In the following experiments, objects to catch are at a distance D which is compared with the length of the robotic arm, R. In this case, $\Pi=D/R$. If D exceeds R, it is impossible to catch the object. Π not only measures a simple geometrical space perception but also spatial representational capacities of the operator. Indeed, to estimate the distance for which the object is not reachable, the operator must transform absolute co-ordinates of the environment into relative coordinates referenced to the arm ([FIT78]).

Other criteria are used. [PAG98] shows that there is no correlation between a verbal judgment and a "motor" judgment of distance perception, in monocular vision. It is thus important to measure motor control, in order to appreciate the real appropriation level of the system by the human operator. To evaluate this motor dimension of remote control, different types of parameters can be used. [VIV91] classifies them into two levels of analysis: phenomenological and behavioral. The first level deals with simple performance evaluation. We have chosen two phenomenological parameters. The success rate corresponds to the ratio between the number of times the operator actually grasps the object and the total number of trials. The second parameter is the mean execution time of a movement. The behavioral level consists in a comparison with a model. Once again, two criteria are evaluated. The first one, inspired by [MAG92], measures a spatial error (S), defined by the deviation of the real trajectory from the ideal one. In fact, this error corresponds to the ratio between the distance covered by the robot (R) and the theoretical shortest distance (T): $S=R/T$. The second criterion concerns the co-ordination between the movement of the arm and the opening of the grip. [JEA84] proposes two criteria to measure this co-ordination. The first one establishes a link between co-ordination and synchronization in cinematic changes of arm movement and grip opening. The number of simultaneous occurrences expresses the appropriation level. The second criterion is the instant time of the beginning of the opening of the grip. The opening of the hand is initiated at the beginning of the arm movement, which reveals a clear anticipation of the grasping of the object.

IV. EXPERIMENTAL RESULTS

This section describes the results of the three experiments evocated above. The first one shows that appropriation exists (Sub-section A). The two other experiments demonstrate that an anthropomorphic situation helps the operator in the appropriation of the remote system. The second experiment compares the levels of appropriation of the system by the operator according to different relative positions of the camera and the arm, using perceptual judgments (Sub-section B). The last sub-section (C) analyses results of motor behavior (perception and action coupling) in remote control, which are complementary of the static conditions of the previous condition.

A. Appropriation evaluation

In this section, the main criterion used is Π, defined in the first part of section III.B. In fact, the issue is to compare R (length of robotic arm) and the maximal catching distance D_m evaluated by the operator. The closer $\Pi_m=D_m/R$ is to 1, the more the appropriation is claimed to be effective. R is easy to estimate. For D_m, it is more difficult. 8 positions are defined according to R. 4 are lower than R, 4 are higher than R: ±1cm, ±4cm, ±8cm, ±13cm. The subject must answer "yes" or "no" to the following question: "Can you catch the object with a simple arm extension?". To obtain the threshold value, each position is proposed 10 times in the five directions (Fig. 1). Once the 80 responses are recorded, Dm corresponds to the distance for which number of yes and no are the equiprobable on each side ([BON86]).

Two experimental configurations are tested. In remote control conditions, the camera is situated on the left of the mechanical arm (Fig. 1), which corresponds to a right anthropomorphic condition. Operators have only indirect information of the scene through camera feedback. In natural conditions, operators are located at the exact position of the robotic arm.

14 subjects, aged between 25 and 30, participated in the experiment. They were split into two independent groups, one for each experimental condition. For the remote control condition, they were trained to grasp objects with the manipulator arm in the same condition as in the experiment one. Four sessions were carried out with a training period of grasping with the robotic arm and an estimation phase. All the subjects were right handed and naïve as regards the objectives of the experiment.

The first major result of this experiment is that there is no significant difference between remote-control and natural conditions ($F[1,12]=3.11$, NS). This result means that the precision level of judgments concerning the "graspability" of a distant object is equivalent in remote-control and natural conditions. Moreover, such accurate spatial representation in remote-control conditions is acquired very quickly: no session effect (learning) can be observed ($F[3,36]=0.48$, NS). That is a first argument in favor of assimilation strategy rather than accommodation strategy for tool appropriation.

With a more precise analysis, a direction effect exists by comparison between the two conditions ($F[4,48]=6.48$; $p<0.003$). Indeed, in remote control condition a direction effect exists ($F[4,24]=10,37$; $p<0.001$) but not in the natural condition ($F[4,24]=2.4$; NS). In fact, for two directions, 0° and 20°, Π_m is lower than 1 in the remote control condition (robotic) and nearly equals to 1 in the natural condition (human).

Two interpretations of these data are possible: either the subject has over-estimated the distances or the length of the arm was underestimated. A number of studies have shown a tendency to underestimate distances by subjects in monocular or limited field vision ([BIN98]). [FOG96] shows that peri-personal

space is similar to circular arcs or spherical portions around the considered organ. But, contrarily to human arm, the Manus® arm, used in this experiment, presents a more important extension radius in 0° direction than on the sides.
This bias explains Π_m variations. If only the numerator of Π_m is taken into account, the representation of extension space of the arm tends towards a circle like human arm. We can deduce that the operator has "transposed" her/his own arm representation onto the robotic arm.
This experiment shows that an anthropomorphic position of the camera, according to the arm, results in the fact that space representation in the remote control situation is similar to that in the natural situation.

B. Relative positions between robotic arm and camera

The previous experimental data show evident signs of appropriation of the remote control system by the operator when its configuration is defined following an anthropomorphic relative position between the arm and the camera. The question is now to test whether appropriation is also possible without an anthropomorphic configuration. Experimental conditions in this case correspond to a progressive deformation of the camera-arm configuration from an anthropomorphic one to a configuration in which the camera positioned at 90° relative to the arm, with an intermediate "bias" configuration, in which the camera is positioned at 45° (Fig. 1).

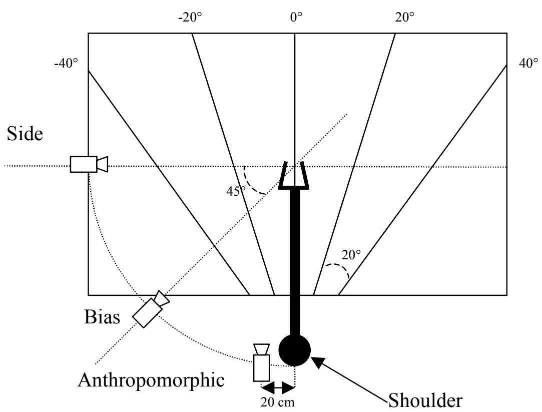

Fig. 1. Experimental device characteristics in the second experiment.

16 subjects, aged between 25 and 30, participated in the experiment. They were split into 4 independent groups, one for each experimental condition (3 remote-control conditions and a natural condition). For the remote control condition, subjects were trained to grasp objects with the manipulator arm in the same condition than in experiment one. Four sessions have been realized with a training period of grasping with the robotic arm and an estimation phase. All subjects were right-handed and naïve concerning the objectives of the experiment.
First, the results show that Π is statistically different according to the remote-control situation ($F[2,9]=9.05$; $p<0.007$). Only anthropomorphic and bias conditions give a precision in grasping space delimitation that is not significantly different from that observed in the natural condition (respectively $F[1,6]=2.48$; NS and $F[1,6]=2.56$; NS). It is also interesting to point out that the standard deviation in the bias condition (0.1) is nearly twice as large as the standard deviation in the anthropomorphic condition (0.06). Moreover, Π in the side condition is significantly different from that in natural condition ($F[1,6]=16.8$; $p<0.006$).
This experiment suggests that the more the system moves away from an anthropomorphic configuration the more it is difficult for the operator to transpose her/his body schema onto the remote-control system.

C. Analysis of motor behavior in remote control

In the third experiment, characteristics of the experimental device are the same as in the second experiment. However, in that case, the study deals with a situation in which subjects are active. The operator is asked to try to grasp an object. The three remote control conditions described above are tested on three independent groups of users.
16 subjects, aged between 25 and 30, participated in the experiment. They were separated in 3 independent groups, one for each experimental condition. They were trained to grasp objects with the manipulator arm in the same condition than the experiment one. Four sessions were realized with a training period of grasping with the robotic arm and a testing phase. All the subjects were right-handed and naïve concerning the purpose of the experiment.
Concerning phenomenological criteria, the analysis of success rate first reveals a session effect for all three conditions ($F[3,27]=10.09$; $p<0.0001$). This effect indicates a progressive adaptation of the operator to the system. Secondly, success rate (successful grasping) is significantly higher in anthropomorphic conditions than in the other two conditions ($F[1,6]=22.58$; $p<0.004$ according to bias condition and $F[1,6]=39.8$; $p<0.0007$ according to side condition). Bias and side conditions are not significantly different ($F[1,6]=1.17$; NS). Thirdly, a direction effect is observed for bias and side conditions with a higher success rate in central directions (-20°, 0° and 20°) (respectively $F[4,12]=4.11$; $p<0.03$ and $F[4,12]=42.23$; $p<0.00001$). However, in the anthropomorphic condition success rate in uniformly high in all directions ($F[4,12]=2.08$; NS). This isotropy is an element in favor of an assimilation process.
The second phenomenological criterion is execution time. It also reveals a session effect ($F[3,27]=32.63$; $p<0.00001$). Secondly, the anthropomorphic condition gives rise to faster movements, as compared to the side configuration ($F[1,6]=6.1$; $p<0.05$) but not compared with the bias condition ($F[1,6]=0.8$; NS). Bias and side conditions are not significantly different ($F[1,6]=2.39$; NS). Thirdly, a direction effect is also observed. Movements in the 0° (forward) direction are significantly faster than in the other directions for the bias condition ($F[4,12]=4.39$; $p<0.02$) and for the side condition ($F[4,12]=51.61$; $p<0.00001$) but not for the

anthropomorphic condition ($F[4,12]=1.58$; NS). Once again, the anthropomorphic condition presents a spatial isotropy.
The first behavioral criterion is spatial error. It is defined as the ration between the distance covered by the grip and the distance corresponding to the direct trajectory. Spatial error varies across sessions ($F[3,27]=10.72$; $p<0.0001$). Grip trajectories are significantly more linear in the anthropomorphic condition than in the side condition ($F[1,6]=6.05$; $p<0.05$), but not different from that observed in the bias condition ($F[1,6]=3.14$, NS). Bias and side conditions are not significantly different ($F[1,6]=0.49$; NS). Again, anthropomorphic condition presents a spatial isotropy, which is not true for the other two conditions.
The second behavioral criterion is the coordination of the movement of the arm and the opening of the grip. The percentage of simultaneous control of grip opening and arm movement increases significantly with sessions ($F[3,27]=5.41$; $p<0.005$). Coordination is better in the anthropomorphic condition compared to the side condition ($F[1,6]=6.94$; $p<0.04$), but not significantly better than that observed in the bias condition ($F[1,6]=0.01$; NS). However, for that criterion, the bias condition gives better results than the side condition ($F[1,6]=6.77$; $p<0.04$). Once again, the direction effect is significant for bias ($F[4,12]=4.22$; $p<0.03$) and side ($F[4,12]=3.62$; $p<0.04$) conditions but not for the anthropomorphic condition ($F[4,12]=4.22$; NS). The similarity of the coordination of the movements of the arm and the opening of the grip in the case of anthropomorphic condition and the natural condition is another argument in favor of an assimilation process. Indeed, human beings initiate an opening of the hand from the very beginning of the an arm movement.
The time of the beginning of grip opening varies according to sessions ($F[3,27]=4.32$; $p<0.02$). Time of beginning of grip opening according to the three conditions increases with the decrease of anthropomorphic level of the system. The anthropomorphic condition does not differ from the bias condition ($F[1,6]=0.87$; NS), but there is a significant difference between the anthropomorphic condition and the side condition ($F[1,6]=7.98$; $p<0.03$).
In the case of perception-action coupling for a grasping movement, phenomenological criteria (success rate, execution time) show that an anthropomorphic condition gives better results than the other two conditions. Behavioral criteria (spatial error, coordination of movements) confirm these results.

V. CONCLUSIONS AND PERSPECTIVES

Optimal control of an external teleoperated device is dependant on an appropriation of the device by the operator, resulting from a successful adaptation of the operator's control schemes to the characteristics of the external system.. [PIA36] has developed a theory proposing two interdependent modes of adaptation: assimilation and accommodation. If the remote system has anthropomorphic characteristics, assimilation should be the preferential mode for its appropriation by the operator.
In the case of a robotic arm with video feedback, the question was to choose the relative position between the camera and the arm. In the first experiment, the idea was to compare the natural human body schema and the body schema including the remote controlled arm. When the relative position of the arm and the camera respects an anthropomorphic relation, the absence of significant difference in the delimitation of corporal space between a natural condition and a condition including the remote controlled arm constitutes a strong argument in favor of the integration of the device into the body schema of the operator. The two other experiments show that an anthropomorphic condition facilitates the appropriation of the system by the user. The second experiment compared different relative positions of the camera and the arm, from anthropomorphic to non-anthropomorphic. Results show that the more the configuration is far from anthropomorphic, the more the precision of peri-corporal space decreases and becomes biased. The last experiment proposed an analysis at the sensori-motor level of remote control. Results show that motor performance is better in the anthropomorphic condition than in other conditions. Our study suggests that static morphological features can interact with the dynamic mental construction of the body schema.
The anthropomorphic aspect of a remote control system is a determining factor for human appropriation of this system. This result is especially important in the case of disabled people whose handicap leads to specific difficulties in the outside world representation. Studies in progress deal with automatic grasping. The idea is to add a camera on the grip. This configuration can not be directl compared wirh an anthropomorphic situation. Feedback information to the user will be studied and designed to obtain a good appropriation of the system by the operator.
In this study, only visual feedback has been taken into account, being the main source of information used in remote control situations. However, proprioceptive feedback is also extensively used in remote control situations. Recent works on haptic feedback are in progress ([COI02], [DUR03]). This approach has two advantages. Firstly, it uses another sensorial vector than video. We can assume that combining two sensorial vectors gives the operator richer information about the environment. Secondly, we suggest that haptic feedback works in a reflex-like manner, whereas video feedback involves higher-level cognitive mechanisms. With telemeters on the grip, the distance to the object can be sent back through a force feedback joystick. That might also lead to appropriation, while maximizing assimilation processes.

VI. BIBLIOGRAPHY

[BER00] Berti, A., & Frassinetti, F. (2000). When far becomes near: remapping of space by tool use. *Journal of Cognitive Neuroscience, 12,* 415-420.

[BIN98] Bingham, G.P., & Pagano, C.C. (1998). The necessity of a perception-action approach to definite distance perception : monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 145-168.

[BON86] Bonnet, C. (1986). *Manuel pratique de psychophysique.* Paris : A. Colin.

[COI02] Ph. Coiffet, & A. Kheddar (sous la direction) : "Téléopération et télérobotique", Chapitre 4: "Retours haptiques" (A. Kheddar) - Octobre 2002, Collection I2C Hermès – Lavoisier, ISBN 2-7462-0447-9.

[COW99] Cowey, A., Small, M., & Ellis, S. (1999). No abrupt change in visual hemineglect from near to far space. *Neuropsychologia, 37,* 1-6.

[CUT97] Cutting, J.E. (1997). How the eye measures reality and virtual reality. *Behavior Research Methods, Instrumentation and Computers, 29,* 29-36.

[DUR03] C. Duriez, C. Andriot et A. Kheddar : "Interactive haptics for virtual prototyping of deformable objects: snap-in tasks case" - EUROHAPTICS, July 5-9 2003, 2003 Dublin, Ireland.

[FIT78] Fitch, H., & Turvey, M.T. (1978). On the control of activity : some remarks from an ecological point of view. In D. Landers & R. Christina (Eds), *Psychology of motor behavior and sport.* Urbana, IL : Human Kinetics Pub.

[FOG96] Fogassi, L., Gallese, V., Fadiga, L., Luppino, G., Matelli, M., & Rizzolatti, G. (1996). Coding of peripersonal space in inferior premotor cortex (area F4). *Journal of Neurophysiology, 76,* 141-157.

[HEA20] Head, H. (1920). *Studies in neurology*, Volume 2. London: Oxford University Press.

[HOC00] Hoc, J.M. (2000). From human-machine interaction to human-machine cooperation. *Ergonomics, 43,* 833-843.

[HOL83] Hollnagel, E., & Woods, D.D. (1983). Cognitive systems engineering : new wine in new bottles. *International Journal of Man-Machine Studies, 18,* 583-600.

[HOP02] P. Hoppenot, E. Colle : "Mobile robot command by man-machine co-operation - Application to disabled and elderly people assistance" - Journal of Intelligent and Robotic Systems, vol. 34, n°3, pp. 235-252, July 2002.

[IRI96] Iriki, A., Tanaka, M., & Iwamura, Y. (1996). Coding of modified body schema during tool use by macaque postcentral neurons. *Neuroreport, 7,* 2325-2330.

[JEA84] Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior, 16,* 235-254.

[JEA97] Jeannerod, M. (1997). *The Cognitive Neuroscience of Action.* Cambridge, MA: Blackwell.

[KAR95] Karsenty, L., & Brézillon, P. (1995). Coopération homme-machine et explication. *Le Travail Humain, 58,* 289-310.

[MAG92] Magenes, G., Vercher, J.L., & Gauthier, G.M. (1992). Hand movement strategies in telecontrolled motion along 2D trajectories. *IEEE Transactions on Systems, Man, and Cybernetics, 22,* 242-257.

[MAR01] Maravita, A., Husain, M., Clarke, K., & Driver, J. (2001). Reaching with a tool extends visual-tactile interactions into far space : evidence from cross-modal extinction. *Neuropsychologia, 39,* 580-585.

[MES05] Mestre D., Rybarczyk Y., Hoppenot P. & Colle E.: "Assistance Robotics: implementation of human-like visuo-motor synergies on a teleoperated mobile device" -. CSUN's 20th Annual International Conference 2005: Technology and Persons with Disabilities. Los Angeles, USA.

[PAG98] Pagano, C.C., & Bingham, G.P. (1998). Comparing measures of monocular distance perception : verbal and reaching errors are not correlated. *Journal of Experimental Psychology : Human Perception and Performance, 24,* 1037-1051.

[PEN02] Pennel, I., Coello, Y., & Orliaguet, JP.: "Frame of reference and adaptation to directional bias in a video-controlled reaching task." *Ergonomics, 45,* 1047-1077, 2002.

[PEN03] Pennel, I., Coello, Y., & Orliaguet, JP.: "Visuokinesthetic realignment in a video-controlled reaching task.' - *Journal of Motor Behavior, 35,* 274-284, 2003.

[PIA36] Piaget, J. (1936). *La Naissance de l'Intelligence chez l'Enfant.* Paris, Lausanne : Delachaux et Niestlé. Translated in 1952 [PIA52].

[PIA52] Piaget, J. (1952). *The Origins of Intellegence in Children.* N.Y.:The Norton Library, WW Norton & Co, Inc. Translation of [PIA36].

[RAB91] Rabardel, P. (1991). Activity with a training robot and formation of knowledge. *Journal of Artificial Intelligence in Education.* USA.

[RAS94] Rasmussen, J., Pejtersen, A.M., & Goodstein, L.P. (1994). *Cognitive Systems Engineering.* New-York : Wiley.

[VAN94] Vanderhaegen, F., Crevits, I, Debernard, S., & Millot, P (1994). Human-machine cooperation : toward an activity regulation assistance for different air-traffic control levels. *International Journal of Human-Computer Interaction, 6,* 65-104.

[VIV91] Viviani, P., & Schneider, R.: "A developmental study of the relationship between geometry and kinematics in drawing movements". *Journal of Experimental Psychology : Human Perception and Performance, 17,* 198-218, 1991.

[VYG30] Vygotsky, L.S. (1930). La méthode instrumentale en psychologie. In B. Schneuwly & J.P. Bronckart (Eds), *Vygotsky Aujourd'hui.* Delachaux et Niestlé.

[WOO95] Woods, D.D., & Roth, E.M. (1995). Symbolic AI computer simulations as tools for investigating the dynamics of joint cognitive systems. In J.M. Hoc, P.C. Cacciabus & E. Hollnagel (Eds), Expertise and Technology : Cognition and Human-Computer Cooperation. Hillsdale : Lawrence Erlbaum, 75-90.