Contribution of neuroscience to the teleoperation of rehabilitation robot

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ABSTRACT

The initial focus of this paper is on the relationship between the human factor and the machine. To be more precise, it is a study on the cognitive problems involved when an operator carries out a remote control action on the environment. Subsequently, the article will proceed to examine how studies on the behavioural neuroscience can bridge the existing gap between the humans and the machines. This gap is categorised as "disembodiment".

In the course of our research, the reduction of the disembodiment was studied in two way. Firstly, from the robot to the human, by evaluating how the implementation of human-like behaviour of the visual anticipation on the steering can improve the robot control. Secondly, the study focused on the human-robot sense, by testing if we can observe appropriation signs of the machine in the body schema of the operator. All the results are discussed in terms of pertinence of the neuroscientific approach for the conception of physical and functional architecture of a teleoperated robot of rehabilitation.

***Keywords* : behavioural neuroscience, rehabilitation robotics, remote-control.**

INTRODUCTION

To allow a disabled person to handle a remote control robot gives him the possibility to enlarge his field of intervention on the environment. However, this situation will involve lots of cognitive problems. They are caused by the fact that the human being can only produce an indirect action on the environment and, in the same way, can only indirectly receives the results of this actions [1]. That means, lots of sensory-motor sensors and their interconnections do not work like in the situation of a direct natural action.

So, even if it is now possible, with the advancement of technology, to retransmit the majority of sensorial modalities (sight, hearing, touch) to the teleoperator, there is still an important gap between the natural dexterity of the human being and that carried out through a teleoperated robot. This gap is, partially, caused by the fact that our capacity of perception of the world can not be summarised by the five senses. We tend to neglect the importance of essential sensorial sensors like vestibulare sensors, that inform us about the body orientation in space, and especially proprioceptives sensors that give information on movement and relationships between the different body elements [2].

It is important to note this late modality, because it defines well the scope of the main problem that a human being encounters carrying out an action by teleoperation. This problem could be summarised by the term "disembodiment". Indeed, proprioceptive sensors are really the main components that give the human being the sensation of belonging. They are the ones which inform the brain about the body position, of its different segments in space, and of their movement dynamics on-line.

According to neuroscientific studies, it is because the human being belongs to a body and acts through this particular body that he can adapt to the world, by constructing his own body schema [3]. But, in the situation of an action carried out in teleoperated conditions this adaptation seems limited, because there are two physically distinct entities.

Nevertheless, it is known that the brain has a very important plasticity that gives the human being a big learning capacity to adapt to lots of new situations. So, it is the study of human capacities to adapt to act through a body that is not his own, that will motivate our future studies. In others words, the question would be to know more exactly the disembodiment level between the operator and the robot, its modulation with the learning time and discover if, in the end, the human body schema extends to the machine.

To do that, a double exploratory strategy has been used (Figure 1). The first, which was categorised as "artificial", was made in a "robot-human" sense and was used to test the improvement of the human-machine co-operation after the implementation of human-like behaviour in working of the robot. The second, which categorised as "natural", was in a "human-robot" sense. It was used to study the eventual appropriation in the human body schema in the course of time.

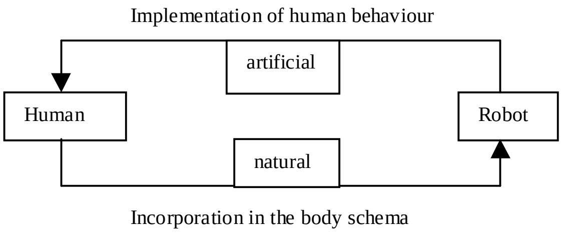


Figure 1 : Model of the principle of "disembodiment" reduction.

The assistive system is composed of a robot and a control station. The robot is able to move inside an indoor environment and take object thanks to a manipulator arm. The control station allows the remote control of the robot by the user (Figure 2).

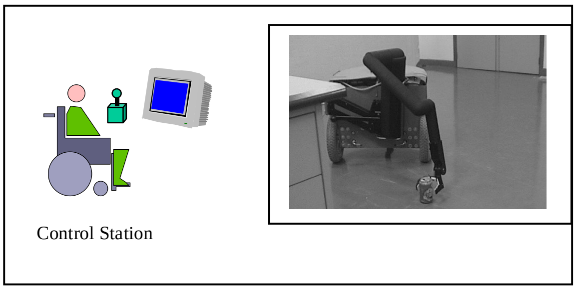


Figure 2 : Assistive system

The first part of the paper is interested in the robot displacement and the second part in the object grasping.

IMPLEMENTATION OF HUMAN-LIKE BEHAVIOUR

A. The example of the visual anticipation behaviour on the steering

In the course of evolution, the brain developed in such as manner as to allow the anticipation of future actions. Moving to escape from a predator or hunting a prey, involves making hypotheses on the world to predict the intentions of others. Thus, it is not a simple reflex, as a passive response to a sensorial stimulus, but on the contrary, the action control necessitates the brain to be a predictor which simulate actions of the others as well as those of oneself.

For example, during the catching movement of a ball, the neurophysiological recordings show that the brain never waits for the sensors to be activated to begin to respond. In this situation, the brain produces a contraction of the muscles, 300 ms before the object touches the hand [4]. In the same way, there are neuromuscular spindles in the muscles which can measure the stretching and which have a sensibility modulated by the brain. This means that the brain can influence the perception at its source and, therefore, the action influences the perception.

Thus, as regards locomotion, the brain acts on the rest of the body in order to organise the movement not from the feet to the head, but from the head to the feet. The head is used by animals like an inertial centre of guidance, stabilised in space from which body movements are co-ordinated. This is due to the fact that this is the part of the body that supports the eyes. Indeed, the gaze is one of the most fundamental components of our steering control in space. It is chiefly by this means a person interacts with the environment, to guide his walking, to avoid obstacles [5].

Therefore, in order to carry out a fast and regular movement, the human being uses the predictive properties of his brain. Hence, neuroscientific studies have showed that when a subject must turn around an obstacle during locomotion, his cephalic axis does not stay aligned with the rest of the body. It appears that for curved trajectories, the head orientation is deviated with respect to walking direction, towards the inner concavity of the performed trajectory [6]. Precisely, the head direction guides the steering by systematically anticipating changes in the direction of locomotion with an interval around 200ms.

1. Modelling. It is this type of fundamental behaviour, of visual anticipation on the walking travel, which has been implemented on the mobile robot. To do that, an analogy has been done between the human gaze and the pan camera mounted on the robot. Therefore, an anticipatory behaviour of the pan camera has been automated according to the steering remote-control carried out by the teleoperator, following the model of the Figure 3. It shows that the camera pan angle must be conversely proportional to the radius curve of the robot trajectory, in order to move the camera towards the tangent point of the imaginary inside curve created by the robot lateral extremity.

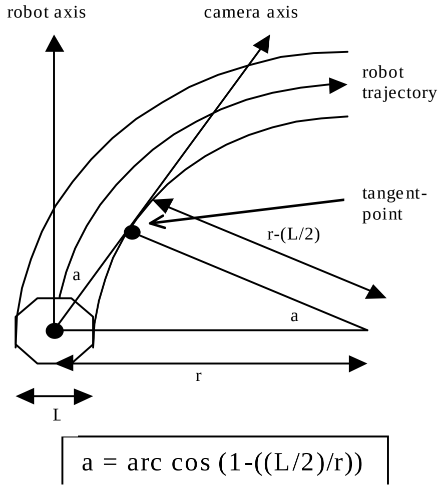
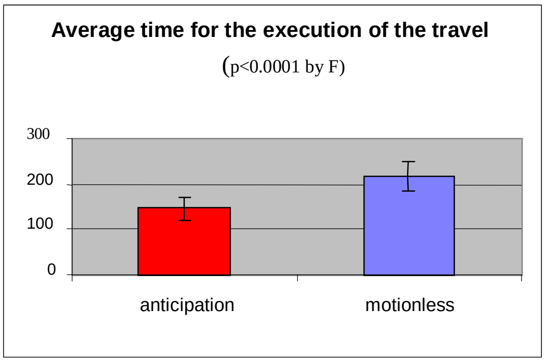
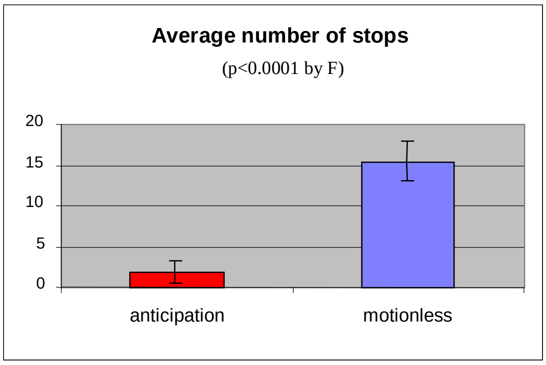


Figure 3 : The camera rotation angle is computed by the curve radius (r) of the robot trajectory, using the trigonometric laws. Here, cos a = (r-(L/2))/r, where the semi-width of the robot equals L/2. The radius (r) is obtained by dividing the translation velocity by the rotation velocity of the robot.

Experimental procedure. The operators were placed in an indirect visual condition. They had to manoeuvre the robot through a slalom route between four boundary marks. These marks were arranged in such a manner that the robot curves were between 90° and 180°. The travel was carried out once in one direction and once in the other direction, in order to prevent the operator from developing a stereotyped travel strategy too quickly. Ten subjects have been tested : two independent groups of five subjects have passed the two main conditions (with or without anticipatory movement of the camera). Groups were independent to avoid a confounded learning effect. After a short trying session, each subject has realised eight testing. The instructions given to the subjects were to carry out the travel, as rapidly as possible, while avoiding collisions with obstacles. For each session, performance was evaluated by computing the execution time of the trajectory, the number of stops, and the number of collisions with boundary marks.

Results. Experimental results show an important advantage of the anticipatory camera condition in comparison with the teleoperator performance in motionless camera condition (Figure 4). Like this, the average time for the execution of the travel is significantly lower with the mobile camera in comparison with the motionless camera ($F[1,78] = 13.9$; $p<.0001$). In the same way, the regularity of robot trajectory is significantly better when the robot is controlled through a camera which anticipates on the steering : for the average number of stops, $F[1,78] = 29.8$; $p<.0001$, and the average number of collisions, $F[1,78] = 9$; $p<.0002$.





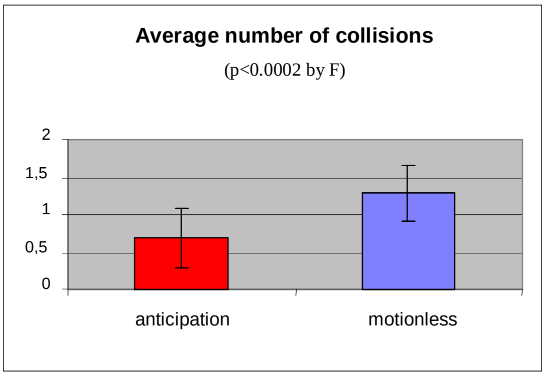


Figure 4 : Experimental results.

Discussion. This data show that it is better to get a visual information on the inside curve of the trajectory, when we have to remote-control a robot though camera vision. In this situation, the operator seems more rapid to execute a travel, has a more secure steering control and a better confidence level in his trajectories. These results agree with the observations done on the human gaze orientation during the locomotion or driving control. In conclusion, the experimental approach which consists of modelling human behaviours, improves the human-machine co-operation by mitigating the "disembodiment" of the teleoperator in relation to the teleoperated robot.

B. Generalisation of human like behaviour

The user pilots the machine through a set of control modes. The role of a mode is the affectation of a command to a degree of freedom of the robot. The source of commands can be the user, the system or both the user and the system. Following that distinction, it exists three types of control modes : manual, automatic or shared modes. The user disposes of a complementary but also partially redundant set of modes which allows the building of strategies adapted to the level of handicap, the user's needs and preferences and the complexity of the task to be performed. As we have seen before, when the robot executes automatic operations its reaction is similar to human behaviour. Such robot response aims at facilitating the co-operation between both entities by facilitating the understanding of the manner the robot operates.

Presently, different control modes have been implemented on the robot, each one of them has a more or less high automation level. This has been made voluntary, in the goal to provide the operator an optimal flexibility in his co-operation with the machine. In fact, if the automation has the capacity to reduce the operator's mental workload, it has negative effects as well. For example, it reduces the attention level or increases his difficulty to regain control after the automatic step of the robot [7].

Therefore, projecting a human being outside the control loop of the machine is the first thing to avoid, if we want to make an efficient automation of a semiautonomous system ([8] ; [9]). In contrary, the operator must ever stay the central part of the human-machine system [10]. He must be actively involved in the task and adequately informed about the general state of the automation ([11] ; [12]). The different automation levels of our robot control modes were made in this manner, which we briefly present in the next paragraphs. The process which develops the manner the modes has been obtained is more precisely detailed in Hoppenot and Colle, 2000 [13].

At first, there are *manual navigation modes* in which the operator controls the robot wheels to guide the displacement. To do that, the person receives a video image, through a camera, and a schematic top sight view of the robot displacement in the room as information feed-back. In this mode, the mental workload of the operator can be reduced by activation of ultrasonic sensors that allow to avoid obstacles, in order that the human being needs only to control the navigation to the final goal. Finally, it is from this mode that has been implemented the human-like behaviour of visual anticipation on the steering.

Next, there are the *visual modes* for which the operator does not directly control the wheels, but the camera direction though which the robot is guided. So, there is a first mode where, if the camera moves, the mobile robot stays in the same navigation angle, and when the camera stops to move in a particular direction, the robot goes in this direction. And a second mode, where the mental workload of the human being can also be reduced, by using a tracking function of the camera that allows to automatically control the navigation by tracking a specific object of the environment.

Finally, we have the less heavy control mode for the mental workload, categorised as *automatic navigation mode*. In this mode, the operator has only to point out an area on the schematic top sight view of the room. Following that, the programme computes the best trajectory that the robot will follow autonomously until the point indicated automatically. However, it is important to note that despite the low cognitive cost of this mode, we have not recorded a better performance compared with the precedent semiautonomous modes. This clearly shows the necessity to continue our research on the shared control modes and particularly the ones based on the human-like behaviour, because they seem to give the best general performance between efficacy and cognitive effort.

RESEARCH OF THE APPROPRIATION LEVEL OF THE ROBOTICS ARM

By definition, carrying out a teleoperation means “indirectly acting on the world”, through a remote-controlled machine. In the case of our rehabilitation robot destined for daily use by disabled people, we can question ourselves about the human capacity for appropriating a robotic-arm which isn’t one’s own. Indeed, if we have good knowledge on the technical efforts made to improve the human-machine co-operation at the interface level [14] [15], as well as the control and function modes of robots [16] [17], little has actually been researched on human efforts made to adapting oneself to machines.

In order to make a first attempt at answering questions on the human capacity to appropriate a machine, we have carried out an experiment whereby a comparison was made between direct and indirect (the use of a Manus robotics arm) human performance in a task of estimating the grasping distance of an object. To be more precise, we have researched the human threshold of precision in estimating the borderline between the peri-spatial field (space surrounding the robot) and the extra-spatial field (space outside of the grasping distance) of the robot, by comparing a person’s precision of estimation of the borderline between his peri-personal space (space surrounding the body) and the extra-personnal space (space outside of a grasping distance).

The relevance of this task is that it involves fundamental neuropsychological concepts of the notion of embodiment. Indeed, studies have showed that this dichotomy between the peri and extra-corporal space is not only descriptive, but has physiological bases too [18]. Besides, this body schema appears to be relatively dynamic because its outline would be distorted by the use of tools [19] [20]. Thus, by utilising direct human performance as reference value, we were able to evaluate if the peri-corporal space of the teleoperator extends, in the same manner, to that of the robotics arm, which would thus be proof of appropriation.

Experimental procedure. The experimental device was composed of a table with four graduated axes. These axes radiated from one of the edges of the table between 40 and –20 degrees, with an interval of 20 degrees between each of them. The convergence point of each axis was centred on the human cephalic axis for direct experimental condition, and on the visual axis of the camera, for indirect experimental condition. Hence, the zero-degree axis was located in front of the visual axis of the human being, like that of the teleoperator. The 40 and 20-degree axes were located on the left of their visual field while the –20 degree axis, on their right. Testing first began on the left arm of the subjects and on a configuration of the robotised system categorised as “left”, which was a situation in which the manipulator robot was located on the left side of the camera. As a control, the experimental device was reversed to test the right arm following this.

The experimental procedure was divided into two stages. The first was the training stage in which the teleoperator, like all humans, evaluated the range capacity of the robotics arm as well as that of his own arm respectively. This was carried out by grasping a cylindrical object placed at different distances on each of the four axes. This stage also served as calibration, in order to find out the real capacities of extension for each of the two arms, and to compare them with estimations given in the next stage. The second stage consisted of finding the threshold distance, according to the condition, for which the subject estimated if the object presented exceeded the grasping distance of his own arm or that of the robotics arm. For this, the experimenter randomly changed the position of the cylinder along each axis and asked the subject to reply "*yes*" or "*no*" to the following question : "Are you able to grasp the object presented by a simple extension of your arm ?".

Results. After the data collection, the "P" ratio of the estimated threshold distances divided by real threshold distances was computed for the different axes and for all experimental conditions. Therefore, Figure 5 represents this "P" ratio distribution according to the four axes, for the human condition and for the "left-arm" configuration of the robot. The first observation was that, although the two curves are not superimposed, there was a statistically significant augmentation of the "P" ratio from 40 to –20 degrees of the experimental space for both conditions (F(3,18)=4,11; p<,0220).

To gauge the level of similarity between the left-arm direct human performance and the performance carried out through the "left-arm" configuration of the robot, the correlation coefficient (r) between the two curves (this coefficient expresses the strength of relationship between two variables from 1, for a perfect positive relationship, and –1, for a perfect negative relationship) was computed. The result of this is r=1. This perfect positive relationship is justified by Figure 6, which represents the "P" ratio of the robot (Pr) to that of the human (Ph) according to the four axes. The director coefficient which was almost equal to zero of the regression line (y=0.0029x+0.9211) of the distribution of these Pr/Ph ratios on all of the axes confirms the similarity between direct human performance and indirect human performance.

To control the validity of this data, an experiment identical to the last one was carried out by asking to subjects to do a perceptive estimation, this time, with reference to extension capacities of his right arm. If our assumption of identification between the operator's arm and the robot's arm is right when the two arms are in the same configuration, a parallel performance must not be achieved (like in the next experiment) but, on the contrary, a crossed performance must be achieved by comparing the ratio of the "left-arm" configuration (Pr) to that of the right-arm (Ph). And indeed, there is a statistically significant difference (F(3,24)=3,68; p<,0259) for the interaction test between Ph right and Pr left according to the experimental axes.

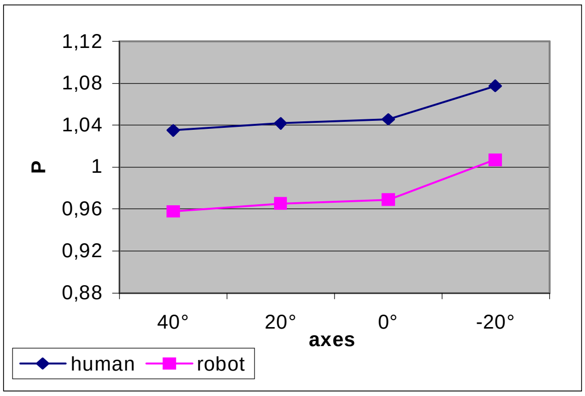


Figure 5 : Ratios P in the left arm situations

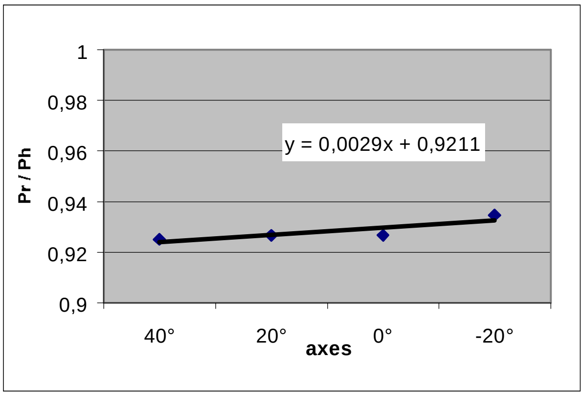


Figure 6 : Ratios P robot on P human

Discussion. The most important result of this study is to notice that the spatial anisotropy of the visio-motor human system seems to be conserved when the human being acts indirectly on the environment, through a manipulator robot. This observation is a strong experimental argument to say that the teleoperator identifies the robot arm as an extension of his own arm. Therefore, this phenomenon agrees with our appropriation assumption of the machine by the human being. If our subsequent research confirms this phenomenon, it will generate important consequences about the visio-motor architecture of a robotics teleoperated system by advocating the importance of making an anthropomorphic configuration to improve the human-machine co-operation.

CONCLUSIONS

These two studies show that it is pertinent to use neuroscientific works to make an optimal system of human-machine co-operation. Moreover, it is very important to note that this is true in different levels of the robotic system. Beginning with the functional level, we observed that the operator felt better when he piloted a robot with human-like reflex of visual anticipation on the steering. Then, when an anthropomorphic configuration has been reproduced for the visio-manual relationship of the robot at the physical level, we note that the operator demonstrated a pattern of response similar to that seen in natural condition.

This strong retention of human characteristics during a remote-control action on the environment, shows that we cannot neglect the anatomo-functional properties of the human operator in the machine conception. This is particularly true of disabled peoples because having a morpho-functionality of their own, this neuroscientific approach will give them an easier utilisation and a better acceptability of this artificial assistance.

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