

RECHERCHES EMPIRIQUES
EMPIRICAL STUDIES

EFFECT OF VISUO-MANUAL CONFIGURATION
ON A TELEROBOT INTEGRATION INTO
THE BODY SCHEMA

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RÉSUMÉ

EFFET DE LA CONFIGURATION VISUO-MANUELLE SUR L'INTÉGRATION DANS LE SCHEMA CORPOREL D'UN ROBOT TÉLÉOPÉRÉ

Les expériences sensori-motrices contribuent à l'élaboration d'une représentation mentale du corps, connue sous le nom de schéma corporel. Ce modèle interne informe plus ou moins consciemment l'individu sur les capacités et limites de ses actes moteurs. Il permet en particulier de délimiter l'espace d'action dit péricorporel (c'est-à-dire jusqu'à la limite d'extension maximale des membres), versus l'espace extracorporel (hors du champ de d'atteinte de ceux-ci). Les travaux en neuropsychologie et neurophysiologie ont cependant mis en évidence que le schéma corporel et, par conséquent, l'espace péricorporel, étaient hautement déformables. En effet, les études expérimentales tendent à montrer que les primates humains et non-humains étendent la représentation interne de leur espace péricorporel, comme une conséquence de l'incorporation de l'outil qu'ils manipulent. Une telle plasticité de la représentation de notre corps peut s'expliquer par le fait qu'un artefact, intégré dans la boucle de contrôle sensori-motrice, est assimilé comme étant un élément à part entière de l'organisme. Jusqu'à présent les travaux scientifiques se sont limités à explorer les interactions directes avec des outils simples (tels que des bâtons ou des râpeaux). Dans ces conditions, les relations perceptivo-motrices sont relativement évidentes et naturelles pour l'utilisateur. Aussi, le premier objectif de cet article est d'étudier si le schéma corporel peut également être altéré lorsque la corrélation entre les actions motrices et leurs conséquences perceptives est plus complexe, comme dans une situation de téléopération. L'intérêt de la téléopération est de permettre une manipulation aisée et précise les relations de contingences entre l'organe effecteur et le capteur sensoriel. L'un des actes moteurs qui va contribuer principalement à l'élaboration du schéma corporel est l'action de préhension visuellement supervisée. Cet acte implique des relations spécifiques de contingences sensorimotrices, internalisées au cours du développement de l'individu. La deuxième question posée dans la présente étude est de savoir si la manipulation de la relation de contingence

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visuo-manuelle aura un effet sur les capacités de l'humain à intégrer un bras manipulateur téléopéré dans son schéma corporel. Pour cela, les sujets ont été placés en situation de contrôle à distance d'un bras robotisé. Les mouvements du robot n'étaient perçus qu'indirectement, à travers une caméra reliée à un moniteur vidéo. La caméra était placée à différents angles relativement au bras manipulateur. La procédure consistait à : (i) évaluer les capacités de l'opérateur à estimer l'espace « d'attrapabilité » du bras avant son utilisation, (ii) laisser les participants manipuler le robot afin d'expérimenter les capacités et limites motrices de celui-ci, puis (iii) répéter la tâche d'estimation de l'espace de préhension du bras après entraînement. L'analyse des données montre (i) que la délimitation de l'espace de saisie peut être aussi précise en situation de téléopération qu'en situation naturelle (avec le bras humain), mais (ii) seulement lorsque la relation caméra/bras respecte une configuration anthropomorphique et que l'opérateur est acquis préalablement une expérience motrice du robot. Ces résultats suggèrent une vraisemblable modification du schéma corporel de l'individu qui se traduit par une extension de l'espace péricorporel, lorsque l'architecture topologique du système téléopéré tend à respecter les contingences sensori-motrices de l'homme. Les conclusions de cette étude sont discutées en termes de conséquences pour le design de dispositifs de téléopération, ergonomiquement adaptés à l'opérateur humain.

Mots-clés : *interaction homme-machine, téléopération, modèle interne, espace péricorporel, plasticité, boucle sensori-motrice*

I. INTRODUCTION

I.1 THE BODY SCHEMA

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 the latter about the consequence of acting in the environment and consequently 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 its parts, in relation with the environment, while moving or resting. 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 their body. In other words, if I am aware that my arm is about 70 cm long then I have the implicit knowledge that my range of action, by simple arm extension, is approximately an arc of 70 cm radius. As motor processes contribute in the first place to the construction of the organism (Berthoz, 1997; O'Regan & Nöe, 2001; Borghi & Cimatti, 2010), a

different sensori-motor processing seems to depend on whether the space considered is reachable or unreachable by hand (Gallese & Lakoff, 2005; Coello & Delevoye, 2007; Witt *et al.*, 2008).

The strongest evidence for distinct representations of near and far space in the human brain comes from neuropsychological studies of patients with neglect or schizophrenia (see Delevoye-Turrell *et al.*, 2010, for review). In many cases, the neglect disorder involves a lesion on the right inferior parietal cortex, especially the supramarginal gyrus (Heilman *et al.*, 1983; Vallar & Perani, 1986; 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; Rafal, 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's 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 a pen to bisect horizontal lines at a distance of 45cm, well within arm's reach. Second, he used a laser pointer to perform a similar line bisection task at a distance of 244cm, well beyond arm's reach. Results showed a pointing deviation on the right side in the first condition and a correct pointing in the second condition. This pattern suggested that the subject had a selective impairment of the representation of the near left sector of space. The second study was conducted by Cowey *et al.* (1994) who 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 indicates that 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 (Quinlan & Culham, 2007; Gallivan *et al.*, 2009; Caggiano *et al.*, 2009). 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, in comparison to far space (see however Previc, 1998, for a description of cortical networks for near and far spaces). Neuro-anatomical substrates dedicated to analyze peripersonal space stretch from the parietal lobe (medial, ventral and anterior intraparietal areas) to the frontal lobe (premotor areas). These circuits are implicated in reaching, grasping and the monitoring of limb movements in relation to the face. The majority

of these neurons have bimodal tactile and visual response properties for a stimulus delivered at a distance of less than about 100 cm in relation to the skin surface (Graziano & Gross, 1995; Fogassi *et al.*, 1996). This bimodal property delimits the well-known “pericorporal” (or peripersonal) sector, where the integration of kinaesthetic and visual information will be facilitated, in order to improve the coordination of limb movements in relation to a corporal frame of reference (Rizzolatti *et al.*, 1997; Previc, 1998).

In spite of this evidence of differential cerebral treatment, depending on whether action space is proximal or distal, people usually are not aware of living in a segmented environment. What could explain the phenomenal continuity of space? A partial answer was 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 showed an increase in 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 (the pathway of the peripersonal system) have a gradient firing response that is stronger in 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).

I.2 TOOL MANIPULATION

Such a fuzzy boundary between spatial sectors suggests, therefore, that spatial layers 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, mainly, on the evaluation of peripersonal space around the hand. To address this question, they have employed, in the majority of cases, the experimental paradigm of tool manipulation (Cardinali *et al.*, 2009; Maravita & Iriki, 2004, for reviews).

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. They found bimodal neurons in the monkeys’ 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 tactile receptive field of the hand. 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. 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 the tool was used. This constitutes further demonstration of the remapping plasticity of the primates' 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, as observed 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 her 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 by referring to neurophysiological data reported by Iriki *et al.* (1996). As 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. Because near space representation was affected by neglect, neglect was also manifested in far space.

A similar remapping of distal as proximal space is demonstrated in patients with cross-modal visuo-tactile extinction (Farné & Làdavas, 2000). This term refers to a clinical symptom, in which 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; Mattingley *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). If a similar cell population exists in humans, a visual stimulus near one hand might thereby enhance 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, relating it to 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 in relation 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 a cross-modal extinction entirely comparable with that obtained in the pre-tool-use condition, showing that the expansion of manual peripersonal space is strictly dependent upon the use of the tool, aimed at physically reaching objects located outside the reaching space of the hand, and it does not merely result from directional motor activity.

Another remarkable proof of the dynamic properties of the body schema comes from the work of Iriki *et al.* (2001). The particularity of this study is that it was carried out in a condition of indirect visual control of the limbs. Here, monkeys were trained to recognize their own hand on a video monitor. Simultaneously, investigators recorded the activity of bimodal neurons having receptive fields localized around the hand. First, results showed that visual receptive fields (vRFs) 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 of 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.

In the experimental study presented in this paper, we investigated whether body-schema deformation exists also when the artefact is remotely controlled. Subjects were placed in a condition of indirect vision, as in Iriki *et al.*’s experiment (2001), and without any direct tactical contact between the subject’s body and the mechanical effector. This remote-control situation of a robotic engine is known as teleoperation. Some studies have reported that, despite the distance, the subject has a feeling of presence or telepresence in the remote space (Held & Durlach, 1993; Loomis, 1993). The interest of this experimental condition is to

prevent any physical continuity between the tool and the operator without destroying the motor communication from the human's nervous system to the mechanical effector's organ. Here, the only sensori-motor linkage existing between the human being and the machine is a visuo-motor relationship. For this reason, we have studied specifically the consequences of a manipulation of the visual relationships between the position of the camera and the robotic arm on the operator's body schema. We can suppose that the modification of the relative position of visual organs in relation to prehensile organs will lead to a distortion of the sensori-motor loop, as compared to the natural situation (Pennel *et al.*, 2003; Tsakiris & Haggard, 2005). The diminution of the rubber-hand illusion when the fake limb becomes misaligned relative to the subject's arm also supports this idea (Pavani *et al.*, 2000; Farnè *et al.*, 2000). Therefore, our main hypothesis was that the remote robot would be integrated into the operator's body schema only if the topological architecture of the camera-arm robotic system was consistent with human sensori-motor contingencies. In order to test this hypothesis, the teleoperated system was configured according to a human-like or "anthropomorphic" architecture, which was compared to two other configurations, progressively departing from this natural organization.

II. MATERIAL

The remote mechanical device used in this experiment was a commercial robotic arm called MANUS (<http://www.exactdynamics.nl/>). This manipulator arm has six degrees of freedom. The distal part is composed of a motorized pair of pliers allowing the user to grasp and manipulate objects in all directions of space. In this experiment, the device was used only in a Cartesian mode of movement. The operator controlled directly the movement of the arm's distal extremity without having to care about the different angular rotations, which were carried out at the level of each articulation, and were necessary to achieve a constant direction of motion of the extremity towards a goal in space. In the Cartesian mode, rotations are computed automatically, by solving an inverse kinematics problem. This mode is assumed to provide the user with a more natural control, with reference to current models of human motor control.

Subjects remotely controlled the MANUS using a control station. The video monitor of the computer interface was 31cm long by 23cm wide. The visual scene was retransmitted on the screen by a camera close to the robot, which had an optic field of view of 50° in the horizontal dimension and 38° in the vertical dimension. In order to allow exchanges of information (control orders to the robot and visual feedback), the control station was connected to the robot by a CAN (Controller Area Network) bus (figure 1). The CAN is a protocol using the industrial serial communication bus that allows command distribution in real time with a high level of efficacy and security. A command order from the

station is transmitted to the control box of the robotic arm via the CAN interface card. This bus transmits different kinds of messages such as the angular position of the arm allowing the definition of its configuration, state messages from the MANUS (warnings, errors...), and the code of action carried out (e.g., joint or Cartesian control mode). This connection bus was used to record information transfers between the operator and the machine. In the present experiment, participants controlled the robot arm through a three-degrees-of-freedom joystick that allowed, in a Cartesian mode, to drive the device instinctively in the three dimensions of space. The arm's motion speed was also manually regulated using this same interface.

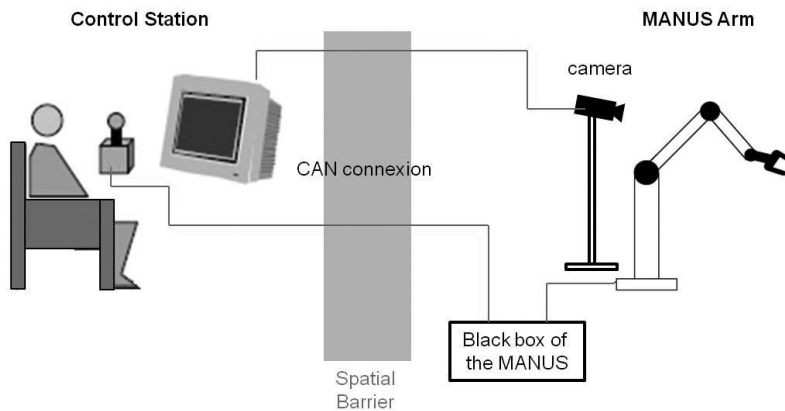


Figure 1 : Architecture du système de contrôle du bras robotisé MANUS.

Les sujets téléopèrent le robot grâce à un joystick. La perception visuelle à distance de l'environnement expérimental, où se situe le bras MANUS, est indirectement réalisée à travers une caméra vidéo qui transmet la scène sur le moniteur de la station de contrôle.

Figure 1: System architecture for the control of the MANUS robotics' arm.

Participants teleoperate the robot using a joystick. The visual perception of the remote experimental environment – where the MANUS arm is located – is indirectly performed through a video camera that transmits the scene to the monitor of the control station.

III. METHODS

Two behavioural assessments were used to evaluate whether or not the body schema of the human operator could be altered in a teleoperated situation. The first assessment involved comparing the participant's performance before and after the manipulation of the robot. The second assessment involved comparing the performance in teleoperation versus a natural situation. The originality of our experiment is thus to reveal body-schema alterations, not through the study of neuropsychological cases, but using behavioural assessments in normal subjects placed in a

teleoperational situation. This assessment is based on the concept of affordance, which describes interaction relationships between an actor (or an effector) and the surrounding environment (Gibson, 1979). Warren and Whang (1987) have proposed a measurement method to describe the attunement of environmental variables to action variables related to the organism. They defined dimensionless number P_i , as a ratio of an environmental dimension to a body dimension. In the following experimental conditions, the object that the subject had to catch was at a variable distance (D) in relation to the robotics' arm length (R). Thus, as distance increased, a critical distance appeared in which grasping by simple extension became impossible, and required a 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 corresponds to a P_i ratio ($P_i = D/R$) of 1.

If we ask an operator to estimate the maximum reachable distance, the value of the P_i ratio will inform us about the operator's representation of space, caused by his/her interaction with the machine. In order 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 the coordinates of the robotic system (Fitch & Turvey, 1978). The P_i ratio thus provides a numerical estimate of the operator's body schema, which can be statistically analysed. This ratio is defined as the subject's estimation of the maximal grasping distance divided by the arm's length. Thus, the closer to 1 the ratio is, the more the individual has a good representation of his/her range of action in space, and therefore, the more his/her body schema conforms to actual action capabilities. Next, two performance analyses are completed: i) a comparison of the P_i ratio before and after using the MANUS telemanipulator and ii) a comparison of the P_i ratio obtained with the subjects in robotic conditions and the ratio obtained with the subjects in natural conditions (i.e., subjects using their own arm). If the P_i ratio calculated for the peribrachial space is getting closer to 1 after the training and is not statistically different between the normal and mediated conditions, results might be interpreted in terms of an extension of the operator's pericorporal space to the remote manipulator's arm length.

III.1 CONDITIONS AND SUBJECTS

Twenty-eight subjects between the ages of 25 and 30 took part in this experiment. These individuals were randomly distributed into four independent groups, yielding seven subjects per experimental condition. In these four conditions, three were teleoperated situations, in which the position of the camera relative to the robotic arm was manipulated. The last condition was called "natural", in which subjects acted and perceived on the basis of their own body's movements. All subjects had normal or corrected-to-normal vision. Subjects were selected according to their laterality, such as only right-handed people were included.

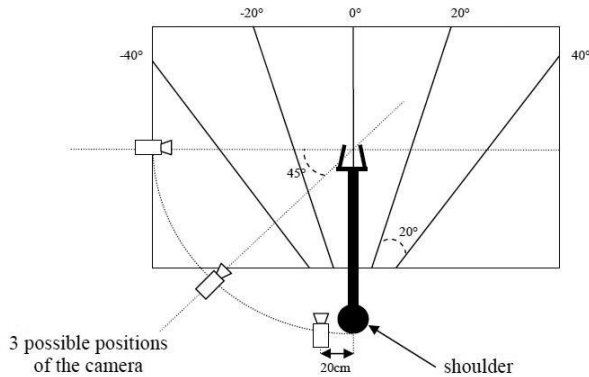


Figure 2 : Détails des caractéristiques du dispositif expérimental (seulement pour les conditions robotiques), en vue de dessus. La caméra pouvait occuper trois positions différentes, par rapport au bras robotisé, selon les trois conditions robotiques expérimental testées. Dans la condition naturelle (non représentée sur la figure), l'épaule du sujet était placée au même endroit que l'épaule du robot, afin de permettre de comparer les résultats entre la condition naturelle et téléopérée.

Figure 2: Details of the experimental environment (only for the robotic conditions), in top view. The camera could be located in three different positions in relation to the robotic arm, depending on the experimental condition. In the natural condition (not represented in the figure), the participant's shoulder was located in the same place as the robot's shoulder in order to allow a comparison between the natural and teleoperated conditions.

To determine laterality, we asked subjects to indicate which hand they always use for completing a manual task. All participants were totally naive about the objectives of this experiment, which lasted approximately one hour per subject. During the experiment, depending on the condition, the robot or the human subject was placed in front of a table. 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 to the experimenter. These straight lines were 20 degrees apart. They stretched out in relation to the median line, which was the 0° ray, on an angular sector, from -40 to 40 degrees (figure 2).

The three conditions of teleoperation were tested and compared with the natural condition. The latter provided us with a reference value for the precision of the human subject's mental representation of his/her pericorporal space. In the three teleoperated conditions, the position of the robotic arm never changed. Only the locations of the camera in relation to the arm changed. The locations of the camera were equidistant relative to the centre of table. 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. The lateral positions of the camera were selected based on two previous studies of the effect of orientation on the rubber-hand illusion (Pavani *et al.*, 2000; Farnè *et al.*, 2000). In these

experiments, the participant's head was immobilized and the position of the fake hand was aligned or orthogonal in relation to the individual arm. Thus, the angle between the gaze axis and the arm axis was 0° or 90° . Moreover, based on Lloyd's (2007) study of subjects' right-hand perception, which showed a nonlinear relationship between the strength of the illusion and the distance of the rubber hand, we decided to test an intermediate position of 45° .

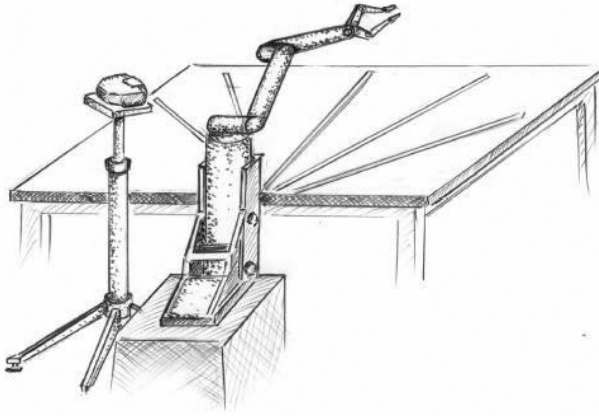


Figure 3 : Représentation schématique de la configuration anthropomorphe, en vue de $\frac{3}{4}$ arrière droit.

Figure 3: Schematic representation of the “anthropomorphic” configuration, in $\frac{3}{4}$ right back view.

In practice, the position of the first camera was located up, on the left, and slightly behind (to compensate for the limitation of camera's optical field of view) in relation to the rotation axis (or shoulder) of the robot (figure 3). This configuration was defined as “anthropomorphic” because it respects the topological relationship between the cephalic organ and the right superior limb of the human being. Thus, this design should be called more specifically “right anthropomorphic” (this is the reason why a sample of right-handed individuals was chosen). In the second condition, known as “bias” configuration, 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 with respect to the antero-posterior axis of the arm, which broke all morphological identity with the human model. This last configuration was called “side” condition. In the “natural” condition, individuals were put exactly in the same location as the robot in relation to the experimental device. This means that their right shoulder was centred in the same position as that of the rotation axis of the robotic arm.

III.2 PROCEDURE

The experimental procedure was divided into four successive steps. First, only participants of the teleoperated conditions had to estimate the reaching space of the robotic arm before any previous manipulation of it. To obtain this estimation, eight object positions were chosen in relation to the reference values (R), which corresponded to the robotic-arm lengths relative to each angular ray tested -- in reality, the arm extension varied slightly in length from one ray to another. The reference values were determined by the experimenter prior to the experiment. During the experiment, the eight positions were symmetrically distributed on both sides of the reference length, yielding four supraliminal and four infraliminal values: $\pm 1\text{cm}$, $\pm 4\text{cm}$, $\pm 8\text{cm}$, and $\pm 13\text{cm}$ relative to the reference (R). The subject's task was to answer "yes" or "no" to the question: "Do you think that you could catch the object presented with a simple arm extension?". To obtain a precise threshold value, each of the eight positions was presented ten times for each of the five rays. The presentation order of object positions and tested rays was randomized for each condition. The 80 answers were analyzed using probit regression to obtain the threshold (S), which was defined as the distance corresponding to 50% of "yes" responses (Bonnet, 1986). Next, the "S" value was divided by the "R" value to calculate the Pi ratio before training, which was compared with the Pi ratio after training.

A calibration step was performed for the natural condition only. In this step, the participant's task was to place the object, held between the thumb and the index finger, as far as possible along each ray by a movement of simple arm extension. Thus, the distance obtained for each ray gives us the reference value (R) of the range of action or peripersonal space for the human arm. This value is also used as a denominator to calculate the Pi ratio for the natural condition, which will be compared afterwards with the Pi ratio for the teleoperated conditions. It is important to underline that the top of the table's surface was completely uniform as the participants cannot use or memorize any visual information to perform the next perceptual reachability judgment task.

In the third step, all subjects had to grasp a cylindrical object, 2.5cm in diameter and 8cm in height, either by extending their right arm or using the robotic arm, depending on the condition. This grasping action was carried out for each ray, from four random positions close to (below and above) the maximal arm-extension length. Thus, subjects were always presented with reachable and unreachable objects in all rays. In both cases, subjects were ordered to try to catch the cylinder as rapidly and precisely as possible by a simple arm extension, i.e., without coupling the arm extension with a movement of the chest. During the entire experiment, the subject's back was kept in close contact with the back of the chair. When the cylinder was unreachable -- which participants did not know until the end of the movement -- they had to completely extend their arm in order to point towards the exact direction of the object. The starting point of each movement

was always the same, the pair of pliers or the main axis of the hand aligned with the ray where the grasping occurred. The execution time was recorded for each experimental condition except for the “natural” condition. The results of this motor task were used to compute an index of movement quality called “spatial error”. This index was defined as the ratio of the movement length of the robot pliers, carried out by the operator, on the shorter distance between the starting point and the arrival point of the movement. The spatial error was computed using only trials in which the cylinder was reachable. The movement length was used to calculate a second P_i value, called P_{i2} , which was defined as the ratio of the estimated distance of catching (D) on the movement length actually carried out by the robot pliers under the subject’s control. In other words, the P_i index was computed from the robot’s arm length (R) – which was quasi-constant – whereas the P_{i2} index was calculated from the robot’s arm path – which was variable from one trial to the other.

The final step was completed by all participants. This step was identical to the first one, which means that it was designed to estimate the threshold distance in which one subject estimated a transition between the grasping space and the locomotion (or out of reach) space. Accordingly, the same procedure was used to determine the threshold (S). In turn, this S value was used to compute a post-training P_i value. The pre- and post-arm-use P_i values were compared statistically. Because the groups were relatively small, a non-parametric (Kruskal-Wallis) statistical test was used.

IV. RESULTS

There was a statistical difference in the execution time of the movement between the three teleoperated conditions ($\chi^2(2) = 8.96, p < 0.02$; Kruskal-Wallis test). A pairwise comparison between conditions showed that the anthropomorphic design allowed faster completion of the movement than the side one ($\chi^2(1) = 4.08, p < 0.05$; Kruskal-Wallis test). However, the anthropomorphic and bias conditions were not statistically different ($\chi^2(1) = 3.02, NS$; Kruskal-Wallis test). The difference between the side and bias conditions was not significant either ($\chi^2(1) = 2.65, NS$; Kruskal-Wallis test). To summarize, there was a general tendency for a greater velocity of movement execution time in the anthropomorphic condition, but the difference effect was significant only for the side condition (figure 4).

As for the execution time, there was a significant difference between the three teleoperated conditions concerning the spatial error of the movement ($\chi^2(2) = 8.91, p < 0.02$; Kruskal-Wallis test). Moreover, pairwise comparisons between the anthropomorphic design and each of the other teleoperated conditions showed a statistical advantage of this condition over the two other conditions (figure 5).

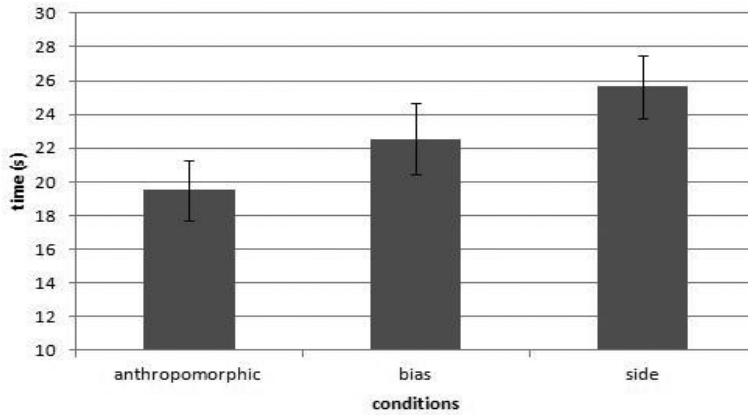


Figure 4 : Temps moyen d'exécution du mouvement selon les trois positions relatives de la caméra par rapport au bras robotique.

Figure 4: Average movement execution times for the three camera positions in relation to the arm.

The anthropomorphic design ensures a more direct movement from the starting to the arrival point than in the bias condition ($\chi^2(1) = 4.00$, $p < 0.05$; Kruskal-Wallis test) and, of course, in the side condition ($\chi^2(1) = 7.84$, $p < 0.01$; Kruskal-Wallis test). No statistically significant difference was found between the latter two configurations ($\chi^2(1) = 1.54$, NS; Kruskal-Wallis test). Thus, for this second motor parameter, an even larger performance improvement between the non-anthropomorphic and anthropomorphic configurations was observed. This indicates that the sensori-motor effort to carry out the catching task is reduced when the arrangement between the visual and manual frames of reference is human-like.

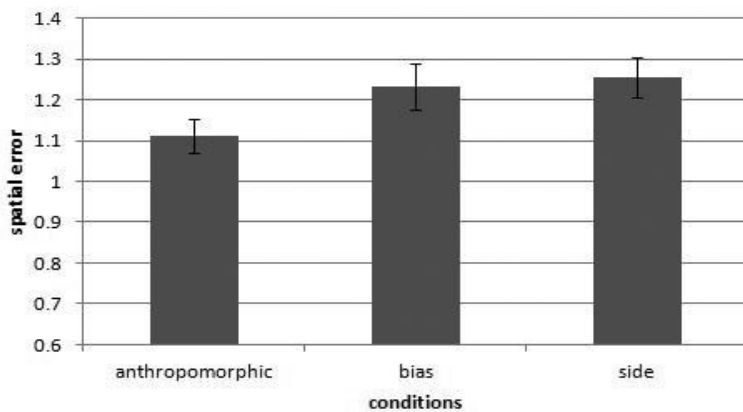


Figure 5 : Erreur spatiale suivant les trois conditions de téléopération.

Figure 5: Spatial error for the three teleoperated conditions.

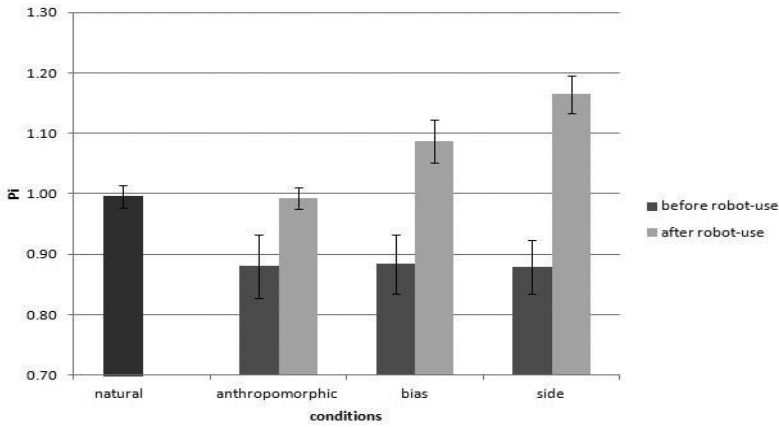


Figure 6 : Valeurs de l'indice Pi d'évaluation de la distance de saisie en fonction de chaque condition expérimentale, avant et après la manipulation du bras robotique.

Figure 6: Pi index values of grasping distance evaluation for each experimental condition, before and after the manipulation of the robotic arm.

From the point of view of the perception task, as shown in figure 6, Pi values of grasping distance evaluation by simple arm extension differed between before and after the manipulation of the robotic arm ($\chi^2(2) = 27.19, p < 0.01$; Kruskal-Wallis test). This difference was observed for each teleoperated condition. The Pi index was found to be significantly lower before robot-use in the anthropomorphic ($\chi^2(1) = 6.07, p < 0.02$; Kruskal-Wallis test), bias ($\chi^2(1) = 9.09, p < 0.01$; Kruskal-Wallis test) and side ($\chi^2(1) = 9.89, p < 0.01$; Kruskal-Wallis test) configurations when these conditions were individually compared with the same configuration, but after the use of the robot. This small Pi means that, before the manipulation of the robotic arm, subjects underestimated the reaching space of the telemanipulator. This underestimation suggests that, in pre-manipulator-use, the individual still bases the operator-robot system on his/her own arm's extension – which is smaller than the robot reaching space – instead of actually taking into account the larger dimensions of the articulated engine. In other words, it seems that remapping of an individual's representation of the new grasping space cannot occur before the individual has maneuvered the robot.

Post-training Pi values were found to differ depending on the teleoperated condition ($\chi^2(2) = 11.73, p < 0.01$; Kruskal-Wallis test). A pairwise comparison between the natural and each robotic condition also showed a difference (figure 6). In the anthropomorphic configuration, Pi was not statistically different from Pi in the natural condition ($\chi^2(1) = 2.37, NS$; Kruskal-Wallis test). This result suggests that, in the anthropomorphic condition, subjects' ability to delimit their grasping space is the same whether the effector organ is their own arm or a teleoperated robotic arm. On the other hand, the Pi values obtained in the bias condition

($\chi^2(1) = 5.69, p < 0.02$; Kruskal-Wallis test) and in the side condition ($\chi^2(1) = 9.98, p < 0.01$; Kruskal-Wallis test) were significantly different from the “natural” Pi. Pi values for the eccentric vision are larger than 1, and their deviations are significantly larger than those obtained in the natural condition. This finding provides further evidence consistent with the hypothesis of an integration of the robot properties into the body schema of the operator, only when the camera/manipulator relationship respects a human-like topology.

The difference between anthropomorphic and non-anthropomorphic conditions, regarding the natural situation, occurs following an elevation of the Pi value from the 1 reference value: the more the teleoperated condition moves away from the anthropomorphic configuration, the more Pi increases. What might explain such an increase in Pi? Careful inspection of the perceptual and motor results shows a very close similarity. We can suppose that the motor performance carried out during the grasping stage of the experiment could have influenced the following perceptual task. To test this assumption, a Pi2 ratio of the estimated distance of catching (D) divided by the movement length executed by the subject was calculated.

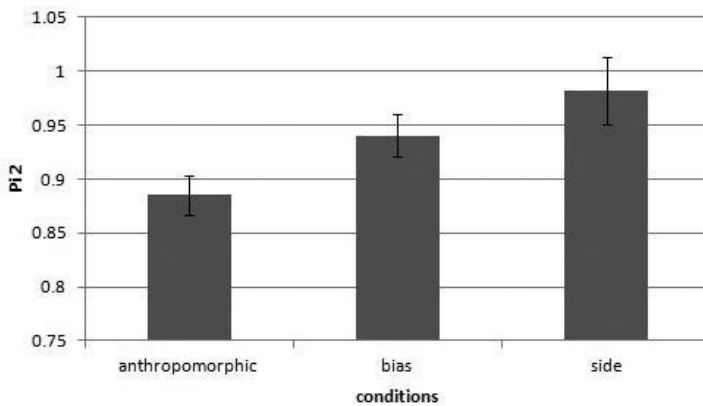


Figure 7 : Valeurs de l'indice Pi2 d'évaluation de la distance de saisie, en fonction des conditions expérimentales. A la différence du Pi précédent, la distance estimée dans ce cas est divisée par la distance réalisée par le bras lors de la tâche motrice de l'expérience.

Figure 7: Pi2 index values of grasping distance evaluation for each experimental condition. Contrary to the previous Pi, for this case, estimated distance was divided by the distance carried out by the arm during the experimental motor task.

Figure 7 shows that, 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. Moreover, this second Pi index decreases linearly towards the anthropomorphic configuration. This outcome may explain the increase observed in the first analysis of the Pi value; it suggests a strong influence of sensorimotor efforts on catching distance estimation,

the more the teleoperated condition moves away from an anthropomorphic configuration.

To summarize, it appears that, in the anthropomorphic condition, the P_i ratio (the ratio of the estimated distance of catching (D) to the robotic arm length) is close to 1, suggesting that the subjects have a precise representation of the robotic arm length. In the side condition, P_{i2} (the ratio of the estimated distance of catching (D) to the length of the movement executed by the subject) is close to 1, suggesting that the actual movement path executed by the subjects has influenced their judgment.

V. DISCUSSION

The experiment presented here aimed to evaluate the influence of camera position in relation to a manipulator arm on the ability of human subjects to integrate a teleoperated system into their body schema. To this aim, various camera/arm configurations designed to correspond to different levels on an anthropomorphic scale were tested and compared. Three camera positions were tested. First, we tested an “anthropomorphic” condition, in which the anthropometric relationship between eye and shoulder position was preserved. Secondly, a “bias” condition was defined, in which the camera was shifted by a 45° angle in relation to the antero-posterior axis of the robot. Finally, in the “side” condition, the camera’s eccentricity was increased in order to be located in a perpendicular position in relation to the antero-posterior robot axis. These three configurations correspond respectively to three progressively decreasing levels of anthropometry.

The results show that the anthropomorphic condition was the only condition to provide a level of precision in grasping space delimitation, which was not significantly different from the performance obtained in a natural condition in which subjects had to gauge the properties of their own arm. This performance was acquired following a short but active training in the manipulation of the electro-mechanical artefact. This means that a human operator, acting on the environment through a robotic telemanipulator tool, can circumscribe his/her range of action almost as precisely as when s/he performs the action with his/her own arm. These findings suggest that the perturbation of the visuo-motor frame of reference involves a remapping of the body representation, as shown in experiments involving prisms (Berberovic & Mattingley, 2003). Moreover, since this remapping occurs after limited training, humans appear to rapidly perceive the affordance of the remote control arm. This provides further evidence that the remapping of functional space does not require extensive tool manipulation (Berti & Frassinetti, 2000; Maravita *et al.*, 2001; Carlson *et al.*, 2010). Therefore, we suggest that a teleoperated device can rapidly be appropriated and incorporated into the operator’s body schema.

As previously mentioned, the results also stress the fact that the body-schema extension has certain limitations, in particular when the topological relationship between the visual and effector organs is too distorted to lead to a perception of “distal attribution”, in which the perceptual experience,

though originating from the stimulation of our sense organs, is referred to as external space beyond the limits of the sensory organs, and does not lead to a sensation of “telepresence” (Loomis, 1992). Such is the case in the bias condition, and even more so in the side condition, for which the results showed that the operator could not have a correct representation of the robotic-arm properties. In these configurations, the Pi index was significantly larger than 1, and larger than observed in the natural situation. This means that the more the operator’s vision is shifted forward and to the side (in relation to the axis of the effector), the more s/he overestimates the maximal grasping distance. The overestimation can be explained by a motor account. The motor task of our experiment showed (i) a linear increase in the arm-movement execution time and (ii) an increase in the spatial error as the eccentricity of the arm increased. Since all conditions were identical except for the relative camera position, the longer execution time and larger spatial error presumably reflects greater difficulties in carrying out the movement when perceptual and motor reference frames differ. Previous experiments have shown a correlation between visuo-motor dissociation and the perceptivo-motor bias (Pennel *et al.*, 2002; Pennel *et al.*, 2003). Assuming a close and reciprocal coupling between action and perception (Wilson and Knoblich, 2005; Bosbach and Prinz, 2007, for reviews), we suggest that the increase in grasping distance estimation in the “bias” and “side” conditions can be explained by an increase in motor effort needed to carry out the grasping task in these situations. Moreover, it is demonstrated that perceived distances increase with motor activity and difficulty (Proffitt *et al.*, 2003; Witt *et al.*, 2004). In the non-anthropomorphic conditions, tool appropriation (as evaluated by the Pi ratio) appears to be reduced, and we suggest that motor performance is used as a metric for perception (Witt *et al.*, 2005).

These fundamental differences between the anthropomorphic levels of each condition suggest that the appropriation process occurs, at least in the teleoperated situation, only under restricted conditions. Our study shows that static morphological features can interact with the dynamic mental construction of the body schema. These results are supported by Botvinik and Cohen’s work (1998). When these authors synchronously stimulated a subject’s hand (hidden under a table) and a visible rubber hand, subjects felt that the life-size rubber hand was their own. Moreover, if the hand was no longer presented in an anthropomorphic position (i.e., the geometric position of the rubber hand being overlaid onto the real hand orientation, as in our experimental definition), the sensation of ownership was greatly reduced (Pavani *et al.*, 2000). Also, the person’s attribution of the fake hand to him/herself decreases significantly with the distance separating the external object from the individual (Lloyd, 2007). The weakening of the rubber-hand illusion as the configuration departs from the anthropometric reference is consistent with our suggestion that the decrease in Pi precision in our experiment can be interpreted as decreased appropriation of the robotic arm by the subject (Haans & IJsselsteijn, 2007).

It might be relatively easy to understand why it is important to keep human geometrical relationships in teleoperation based on an analysis of motor development in children. From an early age, human beings construct

a perceptual assessment of the world and of his/her own body's capacities in relation to his/her anthropometric characteristics (Ledebt, 2001). For example, it was shown in children between 6 and 10 years of age, that the taller they are in absolute value, the higher their crossing-over obstacle limitation; by contrast, when height is expressed as a relative value, the crossing-over limitation remains approximately constant and equal to 88% of the length of the leg, independently of age (Pufall & Dunbar, 1992). These particularities can be observed not only during the execution of a motor task but, also, in purely perceptive conditions. Thus, Warren and Whang (1987) have demonstrated that the visual estimation threshold of the minimal width to walk through a door is based on the eye's position relative to the body's height. This relative gaze height seems to be involved also in the ability to gauge distance (Ooi *et al.*, 2001). Because the organism's perceptivo-motor abilities derive from a calibration process built on the basis of metric relationships between different body segments, there may be an advantage in maintaining these relationships in teleoperation systems.

Apart from the preservation of length ratios, it seems that the conservation of the location and orientation of the effector organ relative to the sensory organ is key to ensuring effective appropriation of a remotely controlled device into the body schema. Consistent with this view, a neurophysiological study of Graziano *et al.* (2000), in which the authors recorded neuronal activity in area 5 – a brain area known to process body posture and movement – in monkeys showed that these neurons fired when the monkey observed an artificial rubber arm, which was seen in the same position as the monkey's real arm, i.e., a situation in which somatosensory and visual information were congruent. As a general rule, an anthropomorphic stimulus (e.g. a human figure) activates areas of the premotor cortex areas which are involved in the processing of pericorporal space, which is absent in the case of a non-anthropomorphic stimulus (Rizzolatti *et al.*, 1996). Our behavioural study agrees with these neurophysiological studies in showing that action-perception coupling leads to particular cortico-motor processing when the subject observes and/or deals with an anthropomorphic configuration. The essence of this particularity can be matched to the fact that executing, observing, or imagining the same human action evokes identical main cortical activity (Jeannerod, 1997). Accordingly, we propose that this singular perceptual-motor correlation is a key component of the body schema. Therefore, the sensory changes produced by, and associated with, various motor actions seem to be the basis of human functioning (O'Regan & Nöe, 2001). For this reason, we argue that the body schema extension, which is necessary to optimally operate a remote-controlled artefact, can occur only if the teleoperated-device architecture is consistent with human sensori-motor contingencies.

This finding has a direct implication for the ergonomic design of teleoperated devices. The typical spatial and temporal gap of a remote-control situation involves a sensori-motor impoverishment that may hamper the correct achievement of the task. One way to minimize its influence on the system's performance is to help the human operator to perceive and understand the remote device's behaviour. According to this approach,

the ideal system should disappear from the field of consciousness and operators should use it as a “natural” extension to their own body. The notion of joint cognitive systems, which was introduced by Hollnagel and Woods (1983) and was further developed by Rasmussen *et al.* (1994) and Woods and Roth (1995), suggests that “the system must facilitate the appropriation of the system response by the operator” (Karsenty & Brézillon, 1995; Rybarczyk *et al.*, 2012, for reviews). This appropriation, or ownership, process was described by Rybarczyk *et al.* (2004a, 2004b) through an implementation of human-like behaviors in the way of which a remote-controlled mobile robot worked. Here, the advantages of the anthropocentric approach are confirmed, from a morphological point of view, by the fact that the operator is better able to evaluate the field of action of the telemanipulator when the relationships between the visual and grasping reference frames is human-like. In this experiment, only visual feedback was taken into account, as it is the main source of information used in remote-control situations. However, proprioceptive feedback is also extensively used in teleoperation. Therefore, a future study will tackle the issue of visuo-kinesthetic contingences in order to determine whether or not the effect observed with vision only is altered when another sensory modality is used by the operator through haptic feedback.

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SUMMARY

Sensori-motor experiences participate in the construction of a mental representation of the body, which is known as the "body schema". This internal model allows the delimitation of the peripersonal space of action – i.e. an area that extends until the maximal length of the limbs – versus the extrapersonal space – i.e. an area that is out of reach for the limbs. However, neuroscientific studies have shown that the body schema is highly deformable. Experimental studies suggest

that human and non-human primates extend their internal representation of pericorporal space to “include” a tool (such as sticks or rakes) which they are using. This article proposes to study whether the body schema can be altered when the correlation between motor actions and their perceptual consequences is more complex, as in teleoperation situations. Remote control is particularly relevant in order to easily, and precisely, manipulate contingency relationships between effector and sensory organs. The main question, which the present study sought to address, is whether the manipulation of visuo-manual contingencies affects the ability of humans to integrate a telemanipulator into the body schema. To address this question, participants had to remotely control a robotic arm. Results indicate an actual extension of the pericorporal space, only when the topological architecture of the teleoperated system tends to respect human sensori-motor contingencies. This finding is discussed in the context of improving ergonomic designs for devices teleoperated by humans.

Keywords: *Human-Machine Interaction, remote control, internal model, pericorporal space, plasticity, sensori-motor loop*

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