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Body Schema Deformation in Teleoperation: Effect of Sensori-motor Contingences

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Neuropsychological and neurophysiological studies have shown that the body schema is deformable. Experimental studies suggest that human and non-human primates extend their pericorporal space internal representation, in such a way to "include" a tool they use. Such plasticity of our body representation might be explained by the fact that an "artefact", integrated into the sensori-motor control loop, is assimilated as being part of the organism. Until now, experiments have been limited to direct interaction with simple tools (like sticks, rakes, etc.). In these conditions, perceptivo-motor relationships are relatively straightforward and natural for the user. The objective of this paper is to study whether the body schema can be altered when the correlation between motor actions and their perceptual consequences is more complex, like in teleoperation situations. In the present study, subjects remotely controlled a robotic arm. Its movements could only be seen through a camera connected to a video terminal. The camera was placed at different angles relative to the robotic arm. Results indicate an actual extension of the pericorporal space, only when the topological architecture of the teleoperated system tends to respect the human's sensori-motor contingencies.

Keywords: human-machine interaction, remote control, internal model, pericorporal space, plasticity, sensori-motor loop

Introduction

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 this latter about our physical capacities. This mental representation of our functional body, created and updated by the central nervous system, is known as the "body schema" (Paillard, 1991). More precisely, the body schema is defined as a mental construction or internal model we have about our body and parts of it, with relation to the environment, in movement or in rest. It is built through experience, thanks to the combination of multi-modal sensations. If, indeed, the individual has a more or less conscious representation of his/her body action capabilities, it implies that he/she must have a more or less precise idea of the limits of this body. In others words, if one have the consciousness that one's arm has a length of about 70 cm, one has the implicit knowledge that one's range of action, by simple arm

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extension, is approximatively an arc of 70 cm radius. As motor processes contribute in the first place to the organism construction (Berthoz, 1997; O'Regan & Nöe, 2001; Borghi & Cimatti, 2010; Gallese & Sinigaglia, 2010), it suggests a different sensori-motor processing, depending on whether the space considered is reachable or unreachable by the hand.

The strongest evidence for distinct representations of near and far space in the human's brain comes from studies of subjects with a well-known neuropsychological disorder called neglect. In a majority of subjects, the lesion involves the right inferior parietal cortex, especially the supramarginal gyrus (Heilman, Watson, Valenstein, & Damasio, 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; Robertson & Marshall, 1993; 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 highly multifaceted architecture for spatial representation (Bisiach, 1997; Vallar, 1998). For the purpose of this paper, the most important type of neglect is sometimes referred to as proximal/distal neglect.

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

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

In spite of these evident proofs of differential cerebral treatment, depending on whether action space is proximal or distal, we do not have the consciousness of living in a segmented environment. What could explain the phenomenal continuity of space? A partial answer has been provided by Cowey et al. (1999), investigating whether the boundary between near and far regions of space is abrupt or progressive. To address this question, they asked neglect patients to perform a series of line bisection tasks at six increasing distances, from 25 cm to 400 cm. Results show an increase in the pointing error at progressively farther distances, suggesting a continuous change from peripersonal to extrapersonal space. In the same way, neurophysiological recordings among animals confirm this overlapping between the two regions of space. So far, it has been shown that neurons in area F4 (pathway of the peripersonal system) have a gradient firing response that is strongest to stimuli within the proximal region and steadily declines as stimuli are placed farther away (Graziano, HU, & Gross, 1997). The receptive field depth of these neurons also progressively expands as the speed of the stimuli towards the body part increases (Fogassi et al., 1996).

Tool Manipulation

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

Iriki, Tanaka, and Iwamura (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 monkey parietal lobe that coded for the schema of the hand, similar to those studied by Graziano and Gross (1995) and by Fogassi et al. (1996). As already discussed, these neurons fire when a tactile stimulus is delivered to the monkey’s hand and when visual objects are presented near the hand tactile receptive field. The most striking feature described by Iriki et al. (1996) was that visual receptive fields of the bimodal neurons could be modified by a purposeful action. Indeed, when the monkeys reached for far objects with a rake, the visual receptive field was enlarged to include the entire length of the rake and 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, Smania, Manfredi, & Berlucchi, 1996; Paillard, 1993). The space now reachable by the prolongation of the hand was enlarged, including part of what had previously been far space, and the spatial relationship between the body and objects was modified by the action of reaching with a tool. As a consequence, far space was remapped as near space and the neurons that fired for near space also fired when what had previously been coded as far space was reached by the rake. Moreover, this extension was reversible, because the elongation of bimodal neurons receptive fields contracted towards the hand after a certain delay after tool use. This constitutes further demonstration of the remapping plasticity of the primate spatial representation.

This modulation of space coding can also be observed in human beings. Berti and Frassinetti (2000) showed in a right brain-damaged patient that, when the cerebral representation of pericorporal space was extended to include a tool used for a purposeful action, the space previously mapped as far was then treated as near, like in monkeys.

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

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

In Farnè and Làdavas’ (2000) experiment, cross-modal visuo-tactile extinction was assessed by presenting visual stimuli far from the patients’ ipsilesional hands, in correspondence of the distal edge of a rake statically held in their hands. The results show that cross-modal extinction was more severe after the patients used the rake to retrieve distant objects with respect to a condition, in which the rake was not used. Again, the evidence of an expansion of peri-hand space lasted for only a few minutes after tool-use. Finally, pointing movements towards distant objects also produced cross-modal extinction entirely comparable with that obtained in the pre-tool-use condition, showing that the expansion of hand peripersonal space is strictly dependent upon the use of the tool, aiming at physically reaching objects located outside the hand reaching space, 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, Tanaka, Obayashi, and Iwamura (2001). The particularity of this study is to have been realized in a condition of indirect visual control of the limbs. Here, monkeys were trained to recognize their own hands on a video monitor. Simultaneously, investigators recorded the activity of bimodal neurons receptive fields localized around the hands. First, results showed that vRF (visual receptive fields) were formed around the image of the monkey’s hand in the monitor. After tool-use, the vRF around the image of the hands on the monitor extended along the image of the handheld rake, like the vRF extension when viewing the hands directly. In other conditions in the experiment, the size and position of the vRFs of these bimodal neurons were modified accordingly with the expansion, compression or displacement of the hands' images in the video monitor, even though the posture and position (and of course the size) of the real hands 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 bodies.

In the experiment study presented in this paper, we have investigated whether the deformation of the body schema also exists when the artefact is remotely controlled. Subjects have been placed in condition of indirect vision, like in Iriki et al.'s (2001) experiment, and without any direct tactical contact between the subject's body and the mechanical effector's. This remote control situation of a robotics' 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, 1992). 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 mechanic effector's organ. Here, the only sensori-motor linkage existing between the human being and the machine is a visuo-motor relationship. It is the reason why we have studied specifically the consequences of a manipulation of the visual relationships between the camera position and the robotic arm in the operator's body schema. It can be supposed that the modification of the relative position of visual organs with respect 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; Haans, 2010, chap. 7). The main hypothesis is that the remote robot would be really integrated in the operator's body schema, only if the topological architecture of the camera-arm robotic system respects human's sensori-motor contingences. In order to test that, the teleoperated system has been configured according to a human-like or "anthropomorphic" architecture, which has been compared to two other configurations, progressively departing from this natural organization.

Material

The remote mechanical device used in this experiment was a commercial robotics' arm called MANUS (assistive robot service manipulator) (retrieved from 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 has only been used in a Cartesian mode of movement. Following this modality, the operator directly controls the movement of the arm's distal extremity without having to care about the different angular rotations, carried out at level of each articulation, necessary to achieve a constant direction of motion of the extremity towards a goal in space. In the Cartesian mode, rotations are computed automatically, via solving an inverse kinematics problem. This mode is assumed to provide the user with a more natural control, and with reference to current human motor control models.

Subjects remotely controlled the MANUS, by means of a computer interface. The video monitor had a dimension of 31 cm long and 23 cm wide. The visual scene was retransmitted on this screen thanks to a camera close to the robot, which had an optic field of view of 50° in horizontal and 38° in vertical dimensions. In order to allow information exchange (control orders to the robot and visual feedback), the control station was connected to the robot by a CAN (controller area Network) bus (see 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 computer keyboard is transmitted to the control box of the robotics' arm via the CAN interface card. This bus transmits different kinds of messages, such as the arm's angular position allowing to define its configuration, state messages from the MANUS (warnings, errors, etc.) and the code of the action carried out (e.g., joint or Cartesian control mode). Finally, it is through this connection bus that the information transfers between the operator and the machine can be recorded.

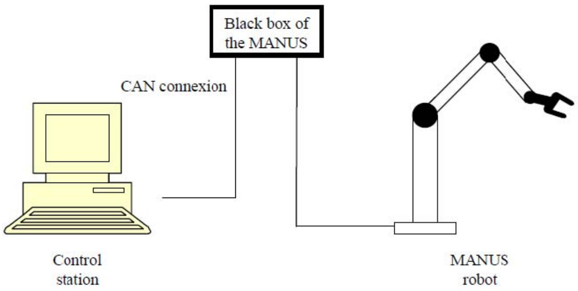

Figure 1. System architecture of control of the MANUS robotics' arm.

Methods

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

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

If we ask an operator to estimate the maximum reachable distance, the value of the Pi ratio will inform us about the operator’s representation of space, caused by his interaction with the machine. Indeed, to estimate the distance, in which an extension of the arm is not enough to catch an object, the operator needs to carry out a translation from absolute coordinates of the environment into robotics’ system coordinates (Fitch & Turvey, 1978). The Pi ratio thus delivers a numerical estimation of the operator’s body schema, on which statistical analysis can be conducted. Pi ratio is thus defined as the subject’s estimation of the maximal distance of grasping divided by the arm’s length. Thus, the more the ratio is close to 1, the more the individual has a good representation of his range of action in space, and therefore, the more his/her body schema conforms to actual action capabilities. Afterwards, in robotic conditions, the Pi ratio obtained when the subject is using the MANUS arm is compared with that obtained in natural conditions (with the subject’s own arm). If the Pi ratio calculated for the peribrachial space is not statistically different between the two conditions, this result might be interpreted in terms of an extension of the operator’s pericorporal space to the remote manipulator arm length.

Conditions and Subjects

Sixteen subjects aged between 25 and 30 years took part in this experiment. These individuals have been randomly distributed into four independent groups, therefore, giving a number of four subjects in each experimental condition. In these four conditions, three were teleoperated situations, in which the camera position in relation to the robotic arm was manipulated. The last condition was called “natural”, in which subjects acted and perceived on the basis of their own bodies’ movements. All subjects had normal or corrected-to-normal vision. Subjects were selected according to their laterality, such as only right-handed persons were included. All participants were totally naive about the objectives of this experiment, lasting about one hour for each subject. During the experiment, the robot or the human being, depending on the condition, was placed in front of a table (see Figure 2). The rotation axis of the subject’s or robotic shoulder was aligned along the median axis of the table. From the centre of this axis radiated five rays, visible only for the experimenter. These straight lines were 20 degrees apart. They stretched out with respect to the median line, which was the 0° ray, on an angular sector, from -40° to 40° (see Figure 2).

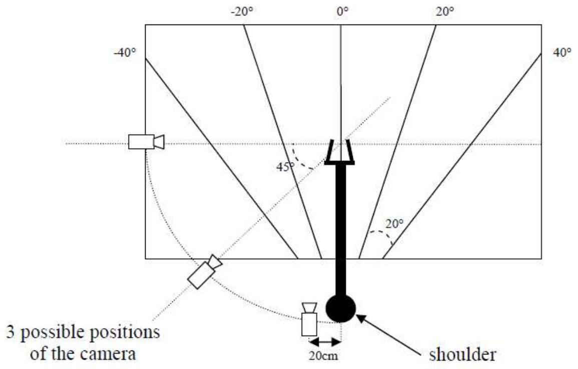

Figure 2. Details of the experimental device characteristics, from top view.

The three teleoperation conditions were tested and compared with the natural condition. The last one gives us a reference value about the precision level of the human’s mental representation of his/her pericorporal space. In the three teleoperated conditions the robotic arm’s position never changed, it was only the camera locations in relation to which it changed. The camera locations were at equidistance with respect to the centre of table. So, they were arranged along a virtual circle of radius equal to the half length of the table. Consequently, it was only the angular position on the circle which distinguished one teleoperation condition from the other.

The first camera position was located up, on the left and slightly behind (to compensate for the limitation of camera optical field of view) in relation to the rotation axis (or shoulder) of the robot (see Figure 3). Such configuration was defined as “anthropomorphic”, because it respects the topological relationship between the cephalic organ and the right superior limb of the human being. So, this design will be called more specifically “right anthropomorphic” (this is the reason why a population of right-handed persons has been chosen). In the second condition, known as “bias” condition, the camera was placed at a bigger eccentricity angle, compared to the first one. This angle was equal to 45° in relation to the ray of 0°. Finally, the last camera was positioned perpendicularly in comparison with the antero-posterior arm’s axis, which broke all morphological identity with the human model. The last configuration was called “side” condition. In the “natural” condition, individuals were put exactly in the same location, relatively to the experimental device, than the robot. This means that their right shoulder was centered on a position identical to that of the robot arm’s rotation axis.

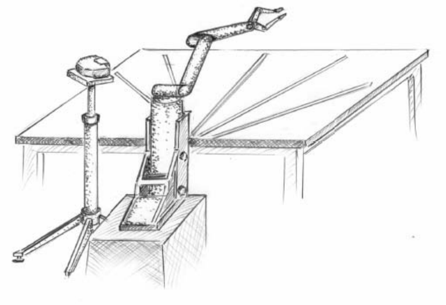

Figure 3. Schematic representation of the “anthropomorphic” configuration, from ¾ right back view.

Procedure

The experimental procedure followed three successive steps. In the first step, each subject had to grasp a cylindrical object, 2.5 cm in diameter and 8 cm high, by extending their right arms or with the robotics’ arms, depending on the condition. This grasping was carried out for each ray, for four random positions close (inferior and superior) to the maximal length of arm’s extension. So, subjects were always confronted with reachable and unreachable objects in all rays. Whatever the case, subjects were ordered to try to catch the cylinder the more rapidly and precisely possible by a simple arm’s extension, that is to say, without coupling it with a chest’s movement. Indeed, during all the experiment, the subject’s back was kept in close contact with the back of the chair. Finally, the starting point of each movement was always the same, the pair of pliers or hand’s main axis aligned with the ray where the grasping occurred. The execution time was recorded in each experimental condition (excepted in the “natural” condition). Also, a last index of the movement quality has been calculated from this motor task. It was called “spatial error”. It was defined as the ratio of the movement length of the robotics’ pliers, carried out by the operator, at the shorter distance between the starting point and the arrival point of the movement. This movement length has been used to calculate a second Pi value, called Pi2, which is the ratio of the estimated D of catching on the movement length executed by the subject, and not the robotics’ arm length, as in the Pi index.

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

The last stage was designed to estimate the threshold distance, for which one subject estimated a transition between his/her grasping space and his/her locomotion space. To do that, eight object positions have been chosen according to the reference length value (R) obtained in the calibration stage. Precisely, these eight positions were symmetrically distributed on both sides of the reference length so as to have four supraliminal and four infraliminal values. Thus, these positions had a value of ±1 cm, ±4 cm, ±8 cm and ±13 cm in relation to the reference (R). Subject's task was to answer by "yes" or "no" to the question: "Do you think you could catch the object presented with a simple arm's extension?". To obtain a precise threshold value, each eight positions were presented ten times for each five rays. The presentation order of object positions and rays tested has been randomised in each condition. Then, the 80 answers have been counted to obtain the S (threshold), which is the distance value in respect of a same percentage of answers "Yes" and "No", equal to 50% (Bonnet, 1986). In order to find the distance corresponding to the response level of 50%, a regression (probit) line was plotted as shown in Figure 4. Afterwards, the "S" value was divided by the "R" value to calculate the Pi ratio, which was compared across the four experimental conditions, using an ANOVA (analysis of variance) statistical test.

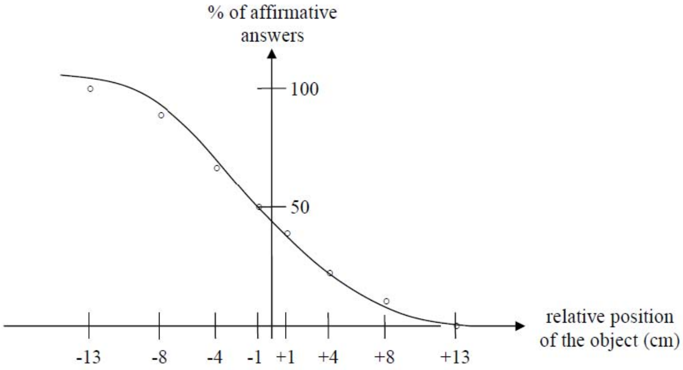

Figure 4. Research method to find the threshold of grasping distance estimation. The threshold value is obtained for a same percentage number of answers "yes" and "no", equal to 50%. In this example, the curve fitted to the subjective data gives a threshold equal about -1cm, with respect to the reference value R.

Results

There is not statistical difference in the execution time of the movement between the three teleoperated conditions (*F* (abbreviation of the ANOVA test) $_{(2, 9)}$ = 2.88; *p* (is the probability of the statistical difference given by the ANOVA test) < 0.10), even if the anthropomorphic condition has the tendency to be the faster (see Figure 5). More precisely, the last one is not statistically different from the bias condition ($F_{(1, 6)} = 0.8$; NS (None significative statistics difference)), whereas it is significantly faster as compared to the side condition ($F_{(1, 6)} = 6.1$; $p < 0.05$). On the other hand, the bias and side conditions are not different ($F_{(1, 6)} = 2.39$; NS). In summary, there is a general tendency for a greater velocity in the execution time of the movement in an anthropomorphic condition, even if this superiority is only significant with regard to a side condition.

As for the previous parameter, there is not significant difference between the three teleoperated conditions, concerning the spatial error of the movement ($F_{(2, 9)} = 3.47$; $p < 0.08$). But, as shown in Figure 6, we can observe the same tendency of the anthropomorphic condition to produce less error than the others conditions. Precisely, the anthropomorphic condition ensures a more direct movement from the starting to the arrival point than in the side condition ($F_{(1, 6)}$ = 6.05; $p < 0.05$), but this difference is not significant in comparison with the bias configuration ($F_{(1, 6)}$ = 3.14; NS). Between these two last conditions, there is not statistical difference ($F_{(1, 6)}$ = 0.49; NS). So, in this second motor parameter, we can observe the same tendency of an improvement of the performance from the side to the anthropomorphic configuration. It means that the sensori-motor effort to carry out the catching task has linearly increased as the camera eccentrics was increased.

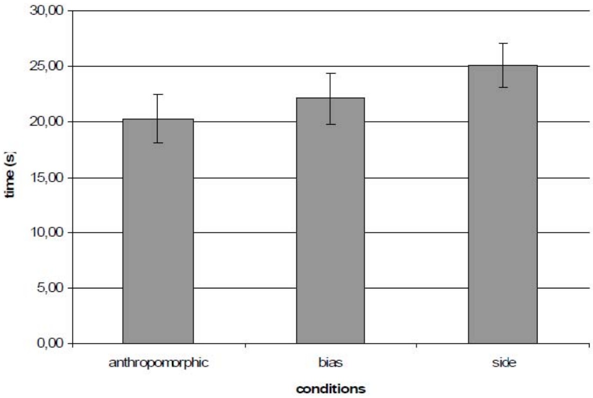

Figure 5. Average times of the execution of the movement following the three relative positions of the camera with respect to the arm.

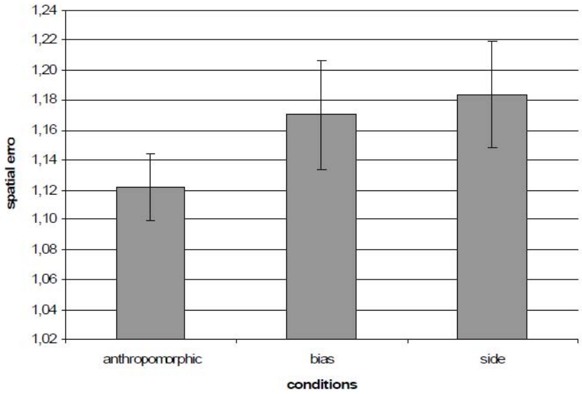

Figure 6. Spatial error according to the three teleoperated conditions.

From the point of view of the perception task, as shown in Figure 7, Pi values of grasping distance evaluation by arm's extension are not the same depending on the teleoperated condition ($F_{(2, 9)}$ = 9.05; $p < 0.007$). That means, they are different from "natural" Pi. In the anthropomorphic configuration, Pi is not statistically different from Pi in the natural condition ($F_{(1, 6)}$ = 2.48; NS). This result suggests that, in the anthropomorphic condition, the capacity of the human being to delimit his grasping space is the same whatever the effector's organ is his/her own arm or a teleoperated robotics' arm.

Pi calculated in the bias condition is not significantly different from the "natural" Pi ($F_{(1, 6)}$ = 2.56; NS). However, in the last case, we can notice that the absence of difference is due, in part, to a large standard deviation (s = 0.1), which is largely greater than the one recorded in the anthropomorphic condition (s = 0.06). Finally, in the side condition, Pi is statistically different from that in the natural condition ($F_{(1, 6)}$ = 16.8; $p <$

0.006). Indeed, Pi values for the side vision are larger than 1, and their deviations are significantly larger than those obtained in the natural condition.

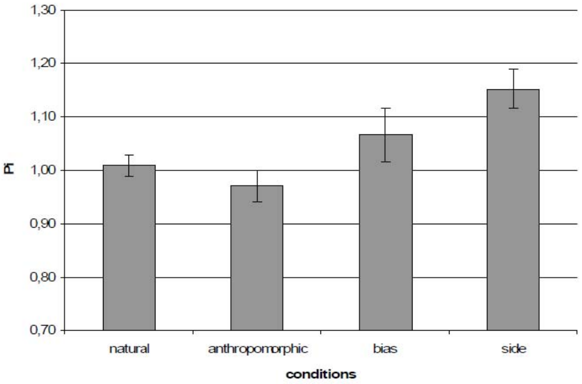

Figure 7. Pi index values of grasping distance evaluation following each experimental condition.

The difference between anthropomorphic and non-anthropomorphic conditions, with regard to 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 increment in Pi? An attentive comparison between perceptual results and motor results shows a very close similarity. We can suppose that the motor performance carried out in the first motor stage of the experiment could have influenced the perceptual following task. To confirm this assumption, a Pi2 ratio of the estimated D of catching divided by the movement length executed by the subject has been calculated.

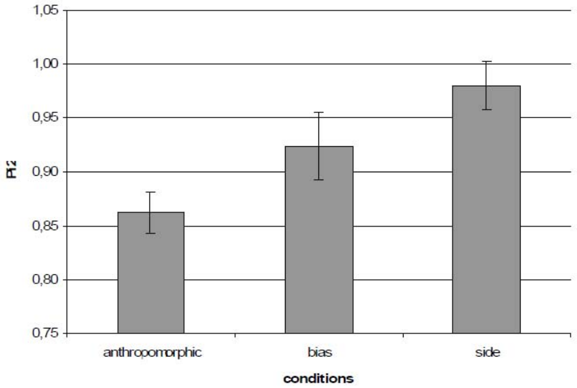

Figure 8. Pi2 index values of grasping distance evaluation following each experimental condition. On the contrary of the previous Pi, in this case, the estimated distance is divided by the D carried out by the arm in the first motor task of the experiment.

Figure 8 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. The last analysis may explain the increase of the first Pi value analysis, by suggesting a strong influence of sensorimotor efforts on the catching distance estimation, the more the teleoperated condition moves away from an anthropomorphic configuration.

To sum up, it appears that, in the anthropomorphic condition, the Pi ratio is close to 1, suggesting that the subjects have a precise representation of the robotic arm length. In the side condition, Pi2 is close to 1, suggesting that the actual movement path executed by the subjects has influenced their judgment.

Discussion

The experiment presented here aimed at evaluating the influence of a camera position in relation to a manipulator arm on the human's capacity to integrate a teleoperated system into his/her body schema. To do that, various camera/arm configurations, designed according to different levels in an anthropomorphic scale, were tested and compared. Three camera localizations were tested. First, we tested an "anthropomorphic" condition, in which the anthropometric relationship between eye and shoulder's position was topologically respected. Secondly, a "bias" condition was defined, in which the camera was shifted by a angle of 45° with respect to the antero-posterior robot axis. Finally, in a "side" condition, the camera eccentricity was increased, such as to be located in a perpendicular position in relation to the antero-posterior robot axis. These three configurations correspond respectively to three progressive decreasing levels, with regard to the human anthropometry.

Results show that anthropomorphic and bias conditions provide a level of precision in the grasping space delimitation which is not significantly different from the performance obtained in a natural condition, where subjects must gauge the capacities of their own arm. It means that a human operator, acting in the environment through a robotics' telemanipulator tool, can circumscribe his/her range of action almost as precisely as when he/she performs the action with his/her own arm. This result suggests that the perturbation of the visuo-motor frame of reference involves a remapping of the body representation as it has been shown in prismatic experiments (Berberovic & Mattingley, 2003). Moreover, since this remapping occurs after limited training, humans appear to rapidly perceive the affordance of the remote control arm. This constitutes further confirmation that the remapping of the functional space does not require extensive training with the tool (Berti & Frassinetti, 2000; Maravita, Husain, Clarke, & Driver, 2001; Carlson, Alvarez, WU, & Verstraten, 2010). From this, we suggest that a teleoperated device can rapidly be appropriated and incorporated into the operator's body schema.

However, the results also show that this body schema extension has certain limitations, in particular when the visual organ/effector organ topological relationship is too much distorted to lead to a perception of "distal attribution", where 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 side condition, in which results show that the operator cannot have a correct representation of the robotics' arm capacities. Indeed, in this configuration, the Pi index is significantly larger (and superior to 1) than in the natural situation. This means that the more the operator's vision is shifted forward and to the side (with respect to the effector's axis), the more he/she overestimates the maximal grasping distance. The overestimation can be explained by a motor account. Indeed, the first motor stage of our experiment shows: (1) a linear augmentation of the execution time of the arm's movement; and (2) an augmentation of the spatial error with the increase of arm's eccentricity. Since, except in their relative camera's position, all conditions are identical, the longer time and spatial error comes from a larger motor difficulty to carry out the movement when perceptual and motor reference frames differ. Previous experiments have shown a linear correlation between the visuo-motor dissociation and the perceptivo-motor bias (Pennel, Coello, & Orliaguet, 2002; Pennel et al., 2003). As we assume a close and reciprocal coupling between action and perception (Hommel et al., 2001), we suggest that the augmentation of the grasping distance estimation in the “side” condition might be explained by an increase of the motor effort to carry out the grasping task in these situations. Besides, it has been demonstrated that perceived distances increase with an augmentation of motor activity and difficulty (Proffit et al., 2003; Witt, Proffitt, & Epstein, 2004). In the non-antropomorphic condition, 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 teleoperated situation, only under restricted conditions. Our study shows that static morphological features can interact on the dynamic mental construction of the body schema. These results are supported by Botvinik and Cohen’s (1998) works. When these authors synchronously stimulate the subjects’ hand (hidden under a table) and a visible rubber hand, subjects came to feel that the life-size rubber hand was their own. Moreover, if this hand was no more presented in an anthropomorphic position (i.e., geometric position of the rubber hand superposed to the real hand orientation—like in our experimental definition), this ownership sensation was strongly reduced (Pavani, Spence, & Driver, 2000). Also, the person’s attribution of the fake hand to her/himself decreases significantly with the distance separating the external object from the individual (Lloyd, 2007). The diminution of the rubber hand illusion, as the configuration departed from being anthropometric, is coherent with our suggestion that the deterioration of Pi precision in our experiment could be interpreted as a reduction of the robot’s appropriation (Haans & IJsselsteijn, 2007).

It might be relatively easy to understand the reason why it is important to keep human geometrical relationships in teleoperation, by the analysis of child motor development.

Indeed, the human being, since his/her early years, constructs a perceptive assessment of the world and of his/her own body capacities with respect to his/her anthropometric characteristics (Ledebt, 2001). For example, it has been shown with children between six and ten years, that the taller they are in absolute value, the more their crossing-over obstacle limitation is high whereas, in relative value, this crossing-over limitation remains equal to 88% of leg’s length, 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 in comparison with the body’s height. This relative gaze’s height seems also involved in our capacity to gauge distances (Ooi, WU, & HE, 2001). Because the organism’s perceptivo-motor capacities derive from a calibration process, built on the basis of metrical relationships between the different body segments, there might be a definite advantage to maintain these relationships in teleoperation systems.

Beyond the respect of length ratios, it seems that the conservation of the location and orientation of the effector organ with respect to the effector organ is fundamental to ensure an effective appropriation of a remotely controlled device into the body schema. This assumption is corroborated by a neurophysiological study of Graziano et al. (2000), where the authors have recorded the area 5 neuronal activity, in monkeys, this area being known to code for body posture and movement. Results suggest that neurons also fire when the monkey observes an artificial rubber arm which is seen in the same posture as the monkey’s real arm, that is, when the somatosensory and visual information are not conflicting. More generally, an anthropomorphic stimulus (e.g., a human figure) generates an activation of the premotor cortex areas implicated in the treatment of the pericorporal space, which is absent in the case of a non-anthropomorphic stimulus (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). Our behavioral study is in agreement with these neurophysiological works, showing that the action-perception coupling leads to a particular cortico-motor treatment 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 ensures the same main cortical activity (Jeannerod, 1997). As a consequence, we propose this singular perceptivo-motor correlation is a constituent of our body schema. Consequently, the sensory changes produced by, and associated with, various motor actions seem to be the bases of the human functioning (O’Regan & Nöe, 2001). It is the reason why we argue that the body schema extension, necessary to optimally operate a remote controlled artefact, can really occur only if the teleoperated device architecture allows a conservation of human’s sensori-motor contingencies.

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