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How do humans mediate with the external physical world? From perception to control of articulated objects.

by

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Abstract

Many actions in our daily life involve operation with articulated tools. Despite the ubiquity of articulated objects in daily life, human ability in perceiving the properties and control of articulated objects has been merely studied.

Articulated objects are composed of links and revolute or prismatic joints. Moving one part of the linkage results in the movement of the other ones. Reaching a position with the tip of a tool requires adapting the motor commands to the change of position of the end-effector different from the action of reaching the same position with the hand. The dynamic properties are complex and variant in the movement of articulated bodies. For instance, apparent mass, a quantity that measures the dynamic interaction of the articulated object, varies as a function of the changes in configuration. An actuated articulated system can generate a static, but position-dependent force field with constant torques about joints.

There are evidences that internal models are involved in the perception and control of tools. In the present work, we aim to investigate several aspects of the perception and control of articulated objects and address two questions, The first question is how people perceive the kinematic and dynamic properties in the haptic interaction with articulated objects? And the second question is what effect has seeing the tool on the planning and execution of reaching movements with a complex tool? Does the visual representation of mechanism structures help in the reaching movement and how?

To address these questions, 3D printed physical articulated objects and robotic systems have been designed and developed for the psychophysical studies. The present work involves three studies in different aspects of perception and control of articulated objects. We first did haptic size discrimination tasks using three different types of objects, namely, wooden boxes, actuated apparatus with two movable flat surfaces, and large-size pliers, in unimanual, bimanual grounded and bimanual free conditions. We found bimanual integration occurred in particular in the free manipulation of objects. The second study was on the visuo-motor reaching with complex tools. We found that seeing the mechanism of the tool, even briefly at the beginning of the trial, improved the reaching performance. The last study was about force perception, evidences showed that people could take use of the force field at the end-effector to induce the torque about the joints generated by the articulated system.

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Chapter 1

Introduction

Many actions in our daily life, such as opening a door, using wine openers, playing musical instruments (e.g. a trombone) and operating forceps in surgery, involve interaction with articulated (kinematically-constrained) tools. In the field of robotics, it has long been recognized that tool interaction is particularly challenging as it requires one to reach the kinematic and dynamical levels of control simultaneously. Depending on the circumstances, these actions can be done with various degrees of precision. In the present work, the objective is to investigate how human perceives the kinematic and dynamic properties in the control of articulated objects.

The capability of using tools is a remarkable milestone in human evolution history. The use and development of even more sophisticated tools has been and still is a motor of human progress. Archaeological records of tool use in human evolution tracks back to 3.3 million years ago, when hominin fossils and stone tools were found in Africa regions (Toth & Schick, 2015). Observations show that chimpanzees, one of mankind closest primate relatives, use of sticks for ant dipping. In particular, chimpanzees can hold a stick with one hand and dip it among the soldier ants at the nest entrance in order to fish them. Chimpanzees are also able to learn to use tools to solve trap problems and make their own tools (Seed, Call, Emery, & Clayton, 2009). For example they can intentionally set out a nutcracker by breaking a branch to get access to food (Boesch & Boesch, 1990).

Although several species are considered to possess tool-use skills, including mammals, birds, fish, cephalopods and insects, the way human makes and uses complex tools is perhaps the ability that sets our species apart more than anything else. Tools are serving as important ***mediators*** between our internal cognitive world and the external physical world. As a matter of facts, skilled tool-use combines multi-sensory perception, cognitive modelling and manual dexterity. It has often been viewed as a sign of higher cognitive ability, or even as the hallmark of the evolution of human intelligence as a more productive way to accomplish daily activities (Osiurak & Massen, 2014; van Schaik, Deaner, & Merrill, 1999; Wynn, 1985). So a fundamental issue is what are the cognitive and sensory-motor basis of human tool use?

The general objective of this thesis is to shed light on the psychophysical aspects in haptic perception and control of articulated tools. Despite its ubiquity in everyday action, human ability in tool-use with articulated objects has been rarely studied. The interested questions involve whether and how our brain integrates information about the geometrical properties of articulated object from two hands in order to build internal model; and investigate the possible ways with which internal representation is developed, that is, the contribution from different sensory inputs (for instance, haptic and visual sensory feedback) in the perception or control of articulated tools.

In this introduction, we review concepts that are important to understand sensorimotor processes involved in the perception and control of action, from simple reaching movement to tool-use.

1.1 Sensory transformations and representations in reaching

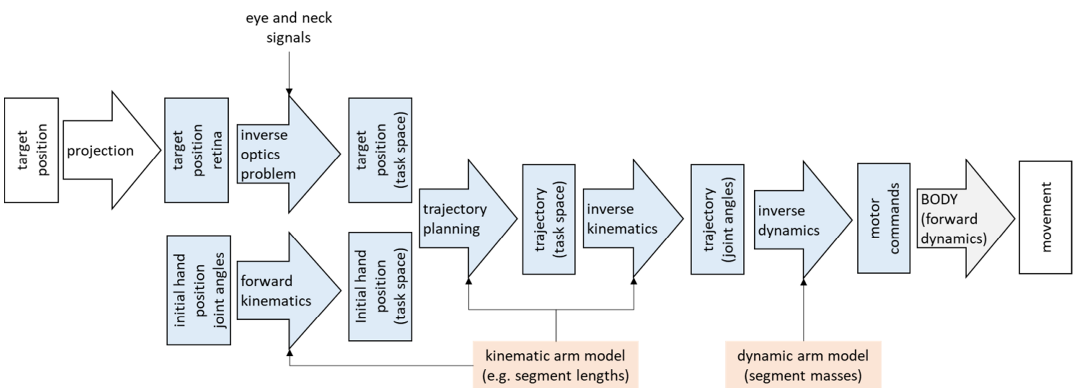


Figure 1. Schematic representation of early transformations involved in the planning and execution of a reaching motion. The blue squares represent signals/representations in the nervous system while the blue arrows represent transformations between these representations. The orange squares represent information about the body (internal models) needed by the transformations.

Motor control, from planning an action to its execution, involves a series of transformations. Taking a simple reaching movement as an example, a first transformation happens when acquiring information about the position of the object (or target) in the environment. This transformation involves the projection of the 3D position of the object on the retina, a 2D representation. Planning and executing the reaching movement also involve computing the motor commands that will move the hand position from its initial position to the object. This process can be quite complex and various control schemes have been proposed to achieve this objective (e.g. see Feldman & Levin, 2009; Latash, 2010) in an alternative viewpoint. An useful idea inspired by engineering consists in decomposing this process into a series of transformation that involves (i) planning the hand movement, (ii) computing the joint angles (arm posture) that corresponds to hand position, and (iii) computing the joint torque and muscle activities necessary to move the hand and arm along the desired trajectory (Atkeson, 1989).

An important observation about human movement in the 2D space is that the hand trajectory tend to be straight, which suggest the trajectory is planned in the Cartesian (task) space (Morasso, 1981). It is important to note that a complex (non-linear) coordination of the shoulder and elbow joints as well as a compensation of interaction torque (dynamic effects) are needed to produce a straight trajectory (Gribble & Ostry, 1999). According to the schema presented in Figure 1, two sensory transformations are needed to plan a movement in the Cartesian space. First, it is necessary to transform the retinal (2D) target representation into a 3D body centered representation (Vindras & Viviani, 1998). This transformation requires knowing the position of the eye and head and computing the distance of the target from the body, an instance of inverse problem for vision (Pizlo, 2001). Second, it is also necessary to know the initial position of the hand in the same 3D space (Baud-Bovy & Viviani, 1998). The transformation of proprioceptive signals coming from sensory afferents (spindles) in the muscles into a 3D representation corresponds to the *forward kinematics* transformation from joint angles (indirectly coded by muscle lengths) into the 3D position of the end-effector (the hand) in robotics. Then, once the trajectory has been planned in the Cartesian space, two additional transformations are necessary to compute the motor commands. The first transformation, which corresponds to the *inverse kinematics* transformation in robotics, transforms the hand position into the joint angles. Finally, the joint angles must be transformed into a set of joint torques and motor commands that move the robot along the desired trajectory according to the *inverse dynamics* transformation of the robotic configuration.

Several of these transformations involve a change of *reference frame*s used to represent spatial information (McGuire & Sabes, 2009; Soechting, 1992). For example, target position is initially represented in 2D eye-fixed reference frame and then successively transformed in a body-centered reference frame and finally in a joint space representation. This schema, while oversimplified with respect to reality, illustrates the fact that the same information can be represented in multiple ways in the brain. It also suggests that representations are closely linked to the processes that connect them and to the goal of the action (Grush, 1997). Moreover, specific computation can take place within a representation or reference frame. For example, trajectory planning is thought to be happen within a Cartesian reference frame (Tamar, Meirovitch, & Barliya, 2013; Morasso, 1981). According to Hubbard (2007), structures, processes, and mappings are the three key elements of a representation. Structure refers to the parts of the model at each level, properties of these structures varying from level to level; process is what and how information is used within a structure; and mapping involves a connection between structures. Cunningham (1989) proposed a method to discover the sensorimotor transformations and representations by the central nervous system by studying errors that occur when the natural mapping between sensory signals and motor commands is artificially transformed by wearing prisms or using a tool for example.

Besides of the information about the target and hand positions in space, it should be noted that the kinematic and dynamic transformations needed to plan and/or execute the movement requires also information about the whole body. For example, solving the inverse kinematics problem requires the structure of the arm and the length of its segments. Similarly, computing in advance of the joint torque to bring the hand to the target requires taking into account the dynamic properties of the body such as the masses of the arm and forearms. Altogether, these information form the so-called internal models of the body, which play a central role in modern accounts of how movements are controlled.

1.2 Internal models and control schemes

The idea of internal models has its origin in control engineering and robotics. In order to describe more precisely the role played by the internal models, it is useful to consider how these terms are used in robotics.

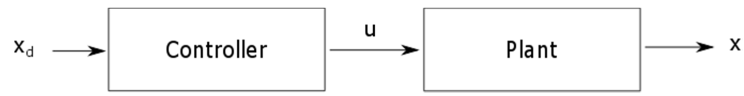


Figure 2. Fundamental element of control system

In control engineering, the fundamental problem of the controller design is to compute the control signals *u* so that the actual behavior *x* of the plant corresponds to the desired behavior x_d. In human motor control, the controller might correspond to the central nervous system and the plant would correspond to the body (see Figure 2). In this case, the control signal *u* represents the motor commands sent to the muscles. Note that the limit is somewhat arbitrary and the spinal cord might be considered, depending on the point of view, as part of the controller or the plant.

In control engineering, the basic control schemes are feedforward control and feedback control, which are described below.

1.2.1 Feedforward control

A ***Feedforward control*** scheme is a control scheme where the controller takes the desired state as input and computes the control signals or motor commands that the plant (or body) needs to reach the desired state. The term feedforward refers to the fact that the information flows only in one direction or, in other words, to the absence of feedback.

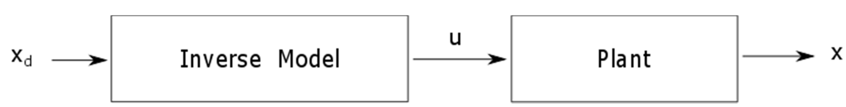


Figure 3. Feedforward control. The inverse model takes the desired value x_d as input and compute the control signal *u* so that the output of the plant *x* corresponds to x_d.

In order to achieve such a result, the controller must perfectly invert the transformation instantiated by the plant (Figure 3), so that the composed action of the controller and the plant corresponds to the identity. For this reason, feedforward control must include an ***inverse model*** of the plant, which takes the desired state of the plant as an input and then computes the control signals (motor commands) that might transform the current state of the plant into the desired one. For example, the transformations described in the previous section involve several inverse models. In particular, the transformation of the desired trajectory into motor commands via the inverse kinematics and inverse dynamics is an inverse model in the perspective of control engineering.

An important issue with feedforward control schemes is that they cannot correct errors or external disturbances. This is a very important problem because it is naturally impossible to have perfect inverse models of the plant, in particular for the human body given the complexity of the musculoskeletal system. Moreover, internal noise and/or external disturbances are likely to cause deviations between the desired and actual movements.

1.2.2 Feedback control

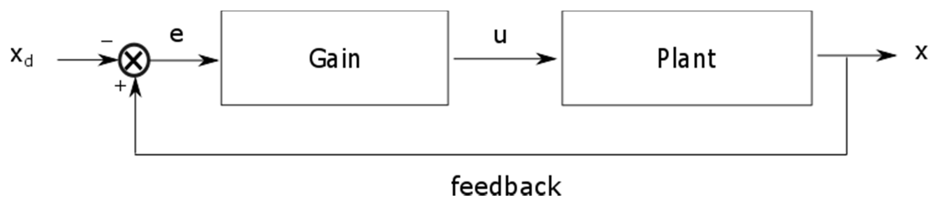


Figure 4. Example of feedback control. x_d refers to the desired value that must be reached by the output x of the plant and u corresponds to the control signals. r is the feedback variable which is the difference between the system output and the desired value. The difference $e = x - x_d$ corresponds to the error signal and is used multiplied by a gain k to drive the plant $u = k\ e$.

Feedback control schemes are an alternative to feedforward control, where the controller uses the current state of the system to compensate for errors from its desired output (see Figure 4).

In human reaching movements, both vision and proprioception provide feedback information that is used to correct and adjust movements. In fact, since Woodworth (1899), reaching movements are thought to be composed of two phases: a feedforward *ballistic* phase followed by feedback *corrective* phase. The initial movement in the ballistic phase would be planned in advance using a ***motor program*** (Keele, 1968) followed by corrective moments driven by visual feedback. Keele (1968) defined motor program as "a set of muscle commands that are structured before a movement sequence begins and that allows the entire sequence to be carried out uninfluenced by peripheral feedback” (p. 387). Visually-driven corrective movement occurs 100-150 ms after the beginning of the movement at the soonest (Desmurget & Grafton, 2000).

In addition to visual feedback, tactile and proprioceptive information are crucial for skilled object manipulation and tool use. In humans, tactile and proprioceptive information is *transmitted to the central nervous system* (CNS) by ascending pathways in the spinal cord (the dorsal column-medial lemniscal system). This system transmits tactile information that is crucial to detect, for example, accidental slip at the fingertip when lifting and adjust the grip force (Johansson & Flanagan, 2009).

A problem of feedback control is that the movement becomes instable when the feedback is delayed. In this case, the feedback information is no more accurate, which can lead to over- or under-compensate the actual error. This problem is particularly important for human motor control given the fact that nerves conduct signals in a relatively low velocity (30-110 m/s), resulting to a transition time of tens or even hundreds of milliseconds. For example, the time necessary to trigger an increase of grip force when a slip occurs in about 100 ms   (Johansson & Flanagan, 2009). In contrast, feedback loop of robots typically operates at frequencies above 1KHz.

1.2.3 Forward model and predictive control

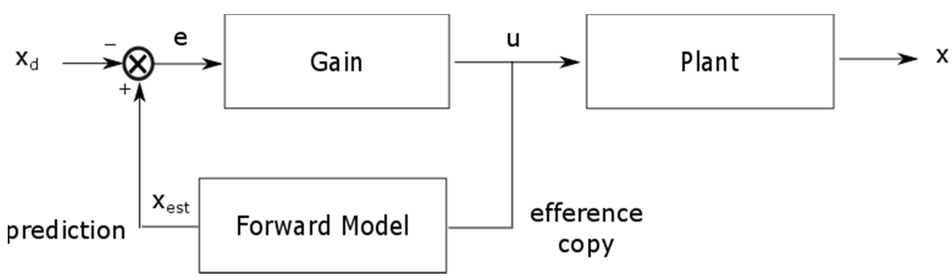


Figure 5. Example of predictive control. The motor system takes an efference copy of the control signals to estimate the state of plant, and use the estimation value as a part of the input in the next-state.

A possible solution to the delay problem in feedback control is to predict the consequence of an action with a forward model (Miall & Wolpert, 1996; Kawato 1999). A forward model simulates the behavior of the body and captures the forward or causal relationship between actions and their consequences. In other words, a forward model takes the control signals as input and computes the expected behavior of the plant given these signals. In human motor control, the outflowing and action producing motor commands generated by the CNS are called an efference. The ***efference copy*** is an internal copy of this signal which is used by the forward model to predict the behaviour of the body (Arbib, 2003). The prediction of the forward model x_{est} can be used in a fast feedback loop to compute the error signal $e = x_d - x_{est}$ (see Figure 5). This loop operates quickly because it does not depend on signals (motor commands and feedback) that must travel to and from the periphery. The efference copy loop can be faster because it operates within the CNS (Desmurget & Grafton, 2000).

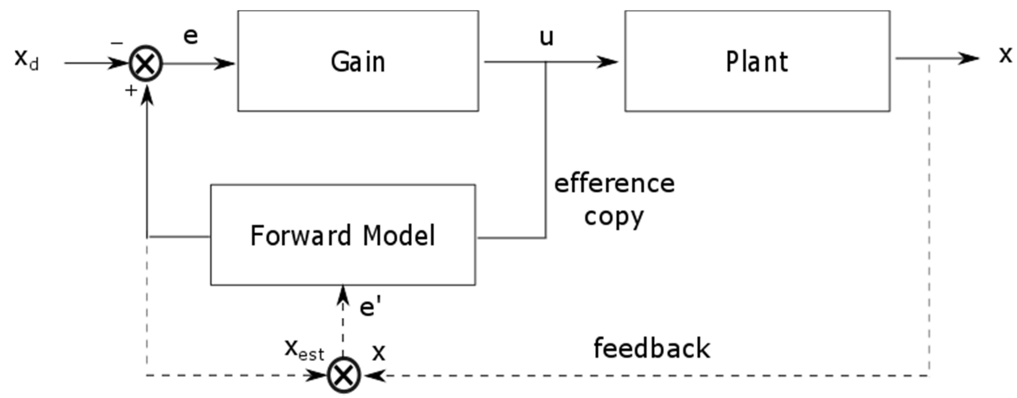


Figure 6. Motor learning. In this schema, the motor command u and forward model are used to predict the state of the system x_{est}. This information is combined with the desired state in a fast feedback loop $e = x_d - x_{est}$. In addition, a feedback signal is compared to the prediction of the forward model in to compute an error signal $e' = x_{est} - x$ that can be used to improve the forward model *(dashed line)*.

This control scheme is an instance of ***predictive control*** in the sense that the forward model predicts the behavior of the plant or body. In order to function well, the forward model must be accurate enough so that the prediction provides useful information to control the body behavior in real-time comparing the predicted motor outcomes to actual performance. In predictive control, the feedback can be used to teach the forward model. In this case, the idea is to use feedback to compare the actual behaviour $\boldsymbol{x}$ of the body with the prediction $\boldsymbol{x_{est}}$ of the forward model to inform the CNS how well the expected action matches its actual external action, $e' = x_{est} - x$ (see Figure 6). Well-established computational learning rules can be used to translate the prediction error $\boldsymbol{e'}$ =

$x_{est} - x$ into changes in synaptic weights which will improve future predictions (Miall & Wolpert, 1996).

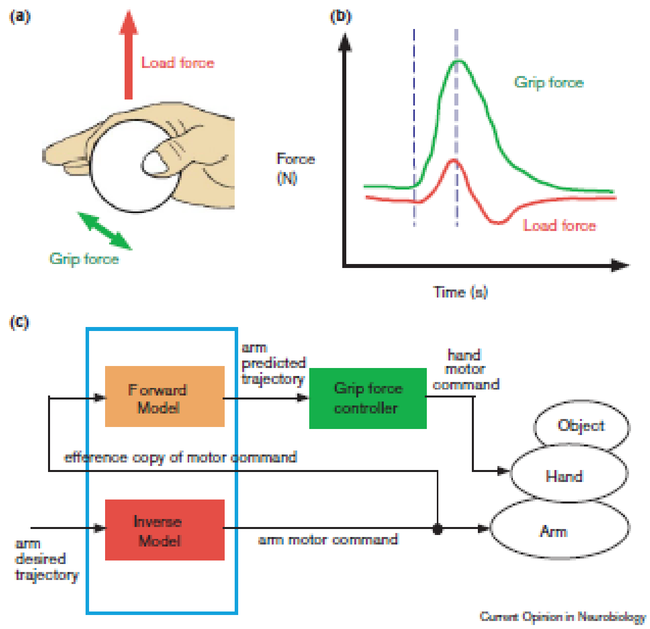


Figure 7. Coordination of grip force and load force, and a computational model based on internal forward and inverse models (Kawato, 1999).

Studies of the grip force when manipulating an object provide a good example of predictive control. These studies have shown that people are able to adjust the grip force in parallel with the inertial load that results from the movement of the arm without delay. The absence of delay suggests that the motor system is able to predict results of an action (e.g Flanagan and Johansson). To explain these findings, Kawato (1999) suggested the CNS uses a combination of the inverse and forward model. With the use of the efference copy the internal model can predict a future hand trajectory, thus allowing to adjust force to the particular load of the known object (Kawato, 1999). In addition, multiple paired forward inverse models describing how diverse objects and environments can be controlled and learned separately have recently been proposed.

Historically, Francis and Wonham were the first to apply internal model in the context of human motor control (Francis & Wonham, 1976). The concept of internal models is now widely used and supported by numerous behavioral studies (Flash & Hogan, 1985; Wolpert, 1997; Gribble, Ostry, Sanguineti, & Laboissière, 1998; Kawato, 1999).

Modern control schemes involve both inverse and feedforward models as illustrated in the previous examples. The general characteristics of these models is to mimic the input and output characteristics of body-environment interaction within the CNS.

1.2.4 Forward model in perception

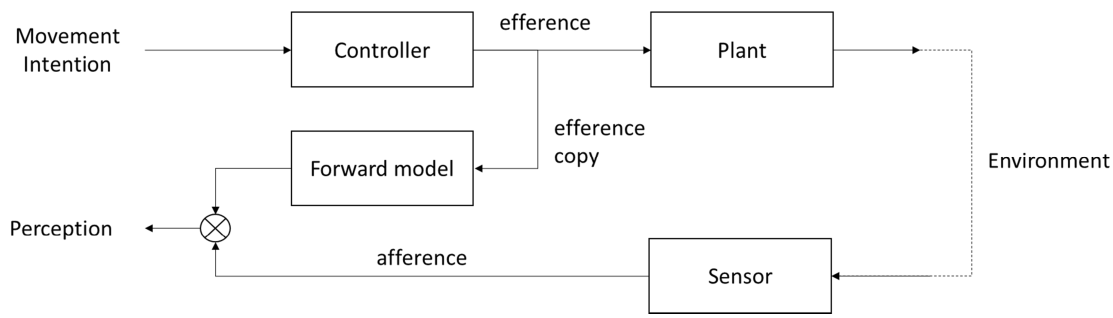


Figure 8. Sensory cancellation. This schema illustrates how the prediction of the forward model might be used to cancel the sensory input. In other contexts, it is thought that the output of the forward model might be combined with the sensory feedback to improve the estimate of the system's state (see text).

Besides of the contribution to motor control, the efference copy and forward model are also thought to play a role in perception (Pickering & Clark, 2014). In particular, the efference copy enables the CNS to compare sensory input (afferences) with predicted consequences of actions in order to distinguish sensory signals that are consequences of an action (reafferences) from sensory signals that are consequences of a change in the environment (exafferences) (see Figure 8). Since Helmholtz, such a mechanism is thought to play an important role to distinguish situations where the displacement of a target on the retina reflects a movement of the eye or a movement of the target in the space (Helmholtz, 1867). In other words, the sensory prediction might be used to cancel the sensory input when the afferent signal results from an action (von Holst, 1954) . This idea of ***sensory cancellation*** has been used to explain, for example, why tactile sensitivity might decrease when one moves (Blakemore, Wolpert, & Frith, 2000; Cullen, 2004). More generally, such a mechanism might play a central role in the *perceptual stability* of the external world in face of the constant changes of sensory inputs induced by body movements (Gallistel, 2013).

Besides sensory cancellation and perceptual stability, the efference copy might also be simply combined with afferent signals to improve estimate of the current state of the body (Baynes, 2009). For example, it has been proposed that efference copy and forward model play a role in proprioception, that is in the perception of one's own movement (Matthews, 1982). Similarly, the efference copy might give information about the weight of objects that are lifted or about external forces that are resisted (Shergill, 2003).

1.3 Haptic perception and the body schema

The term "haptics", from ancient Greek *haptikos* ‘able to touch or grasp' refers to perception through touch and manipulation of objects with the upper limb and the hand (El Saddik, Orozco, Eid, & Cha, 2011). It has also been described as “the sensibility of the individual to the world adjacent to his body by the use of his body” (J.J. Gibson, 1966). On the sensory side, it involves tactile perception through the skin and kinesthetic perception via joints and muscles receptors. Unlike the other four senses (vision, audition, gustation, olfaction), the receptors are not centralized on specific organ but distributed over the entire body. An important characteristics of haptic perception is that it involves movements (***exploratory procedures***) that are specific to the object material and/or spatial properties of interest (S. J. Lederman & Klatzky, 2009). In other words, haptic perception is an active sense, which has also been called ***Active Touch*** (J.J. Gibson, 1966) by opposition with passive touch, where the stimulus is placed on the skin. As such, haptic perception is closely related to the proprioception and kinaesthesia.

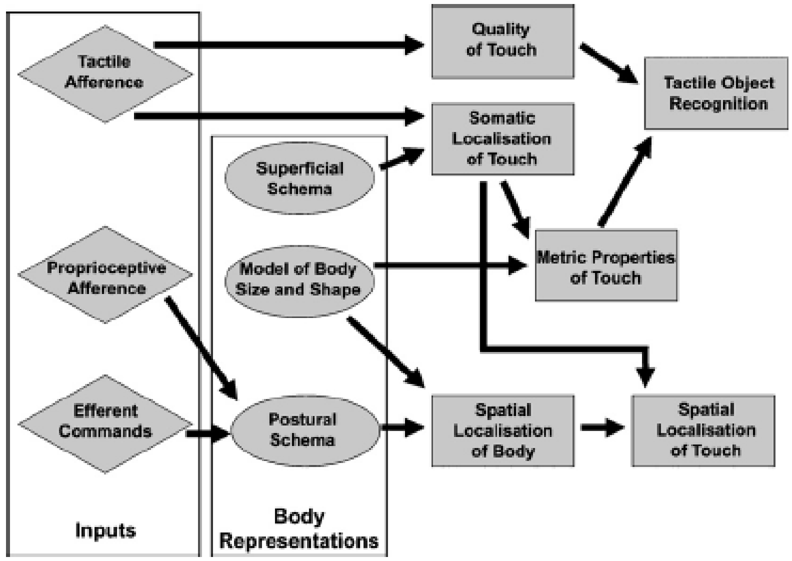


Figure 9. A model of somatoperceptual information processing, highlighting the role of body representations in the construction of somatic percepts. Inputs are depicted as diamond shapes, body representations as ovals, and perceptual processes as rectangles. (Longo et al. 2010 Neuropsychologia)

Haptic perception involves multiple representations of the body and processes. In the somatoperceptual information processing scheme proposed by Longo et al. (see Figure 9), proprioceptive afferents and efferent commands act on the postural scheme, which together with body size information, yield information about the body position (Longo, Azañón, & Haggard, 2010). This information combined with tactile information caused by the contact with an object lead the haptic localization of the object position in space and, possible, the knowledge of its shape via exploratory movements. Tactile afferent might also provide information about the material and superficial properties of the object (softness, texture, temperature, slipperiness, etc.).

The haptic system relies on a complex set of representations and processes, which might also be involved in the body schema. The **body schema** is a concept in cognitive neuroscience that refers to body representations that are used and involved in action planning and execution (Cardinali, 2011). The term was originally coined by Head & Holmes as “organised models of ourselves” (1912). Another early definition is “A combined standard against which all subsequent changes of posture are measured, before the changes of posture enter consciousness" (Schilder, 1935). The body schema is a dynamic representation of the body that is play a role in the control and perception of one's own movement and that function is mostly unconsciously. It represents the position and configuration of the body as a volumetric object in space, and is updated with movement (Haggard & Wolpert, 2005).

From a motor control point of view, the body schema containing information about the body size and body masses implements the processes that transform joint angles to spatial position and vice-versa. The body schema might also be involved in the processes to predict the sensory consequences of our action and in predictive control (see above).

1.4 Tool use

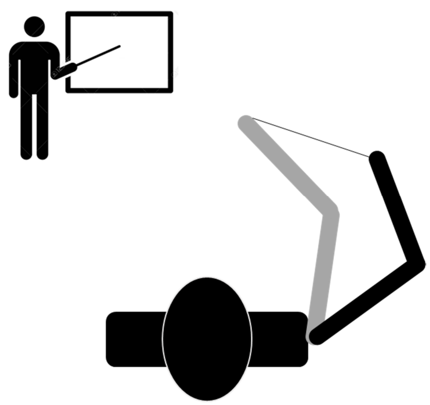


Figure 10. Change of posture required to reach the same position in space with a stick.

Using a tool as important consequences from a control and perceptual point of view because it transforms the relationship between one's action and the environment. For example, reaching a position with the tip of a cane requires a different action than reaching the same position with the hand. Similarly, perceiving the position of the tip of a cane requires taking into action the length of the cane. As shown in Figure 10, using a tool implies the change of the inverse and forward transformations and models involved the planning and execution of movement (e.g. the number of links, the size of the links, etc.). In other words, reaching or pointing with a hand-held tool requires ***adapting the motor commands*** to the change of position of the end-effector, which corresponds to the tip of the tool.

Remarkably, many studies have shown that our motor system can flexibly adapts to specific tool transformations. For example, Ganesh et al. (2014) looked at the immediate impact of using a simple tool on ***pointing accuracy***. They observed subjects overshot the target, and suggested that this pattern of error can be seen as a shortened upper limb representation resulting from the tool use. It is somewhat at variance with the plain observation that one is able to switch between using a long stick or using a short pen to point accurately on a board seemingly without any difficulty (Ganesh et al., 2014).

There has been long-term debates on whether ***precise mental models*** of the concrete tool at hand are needed, with information about the tool's physical properties and mechanics knowledge (precise representation model), or representations for guiding a tool-use action are abstract in the CNS (abstract interval transformation model) (Massen, 2013).

Neuroscientist and neuropsychologists have suggested that tools are incorporated into the body schema, and as a result the representation of the reaching space changes (Berti & Frassinetti, 2000a; Cardinali, 2011; Cardinali et al., 2009; Maravita & Iriki, 2004; Maravita, Spence, Kennett, & Driver, 2002a; Martel, Cardinali, Roy, & Farnè, 2016; Paillard, 1999). For example, it has been suggested that using tools (e.g. mechanical grabber) that physically extends the arm length can modify the somatosensory representation of body morphology, leading to an elongation of the corresponding part in the body schema with the results of extending the perceived size of the reaching space (Cardinali et al., 2009). Another possibility is that tool representation of the mapping between the hand movements and the end effectors in external environment is at a central level enabling preparation and planning of the movement in advance (Massen, 2013). Tool representation is conceptualized as distinct action schemata that encodes (Massen, 2013). Tool representation is conceptualized as distinct action schemata that encoded the varied mapping between hand and the application of the tool (Norman and Shallice, 1986; Baber 2006). The ability to take into account this sensory motor transformation when planning and executing an action with a tool is crucial for its success.

1.4.1 Neuronal bases of tool use

Functional neuroimaging studies have shown that widespread bilateral parietal, temporal, and frontal regions are involved in tool-related performance (Buxbaum, Shapiro,

& Coslett, 2014). Geldenberg and Spatt retrieved the *functional knowledge* from semantic memory, *mechanical problem solving* and use of everyday tools and objects they found that the functional contribution of parietal lobe is associated with comprehension of functional associations between objects and tools, rather than the selection of grip or appropriate use of the tool (Goldenberg & Spatt, 2009). In contrast, in an fMRI study conducted by van Elk wherein participants had to *predict the subsequent* use of a presented tool, results indicated that the left inferior parietal lobe might store hand-posture representations that can be used for planning tool-directed actions as well as for predicting other's actions (van Elk, 2014).

Some addressed tool-related brain region issues by investigating tool use disorders in left brain-damaged patients. Baumard *et al.* suggested that the core deficit resulting in left brain-damaged (LBD) patients with apraxia of tool use is the loss of mechanical knowledge (Baumard, Osiurak, Lesourd, & Le Gall, 2014). Lesion analyses for the LBD patients during a hammering action suggested that inferior frontal areas were particularly responsible for impaired performance, whereas right-brain damage (RBD) patients performed normally in most kinematic task aspects (Hermsdörfer, Li, Randerath, Roby-Brami, & Goldenberg, 2013). Buxbaum *et al.* proposed a componential neuroanatomic model for characterizing the posture and kinematic components for gesture action tasks: for left hemispherical stroke patients, lesioned voxels in the left posterior temporal gyrus were associated with poor performance in posture of tool-related gesture tasks, whereas lesions in left inferior parietal and frontal regions were associated with kinematic component of gesture tasks in imitation of meaningless movement (Buxbaum et al., 2014).

1.5 Articulated objects

The focus of this thesis is on articulated objects or, more precisely, linkages. By definition, a ***linkage*** is an assembly of links and joints in order to provide a desired output motion in response to a specified input motion (Slocum, 2008). A node is an attachment of a joint to a link, and links can have one or more nodes (strictly speaking links must have at least two nodes but we will consider links with one node where the other extremity is held by the user). A *joint* is a connection between two or more links at their node, which allows motion to occur between the links.

Figure 11. Examples of linkages. Connection between two or more links at their nodes, which allows motion to occur between the links (Slocum, 2008; 2017 CCCME; kisspng.com).

In this thesis, we will consider linkages with revolute and prismatic joints. Both joints allow only a single degree-of-freedom movement. The number of degrees-of-freedom (DOF) of a linkage depends on the number of joints and the structure of the mechanism. For a planar mechanism, the number of degree-of-freedom is given by Gruebler's formula:

$$F = 3(n-1) - 2f$$

where n is the total number of links (including a fixed or single ground link) and f is the total number of joints. The number of degree-of-freedom is equal to the number of input motions needed to define the linkage motion.

Articulated objects have kinematic and dynamic properties that distinguish them from rigid bodies, which raise new issues both on the perception and control sides. Unlike rigid bodies, articulated objects do not have a fixed shape since they are made of parts that can move one relative to another. However, these movements are not completely free because the linkage structure constrains the movement of the links along some directions.

In many mechanisms, all links move together in the sense that position of one link determines the position of all other links. In other words, the movement of the whole mechanism might be determined by the movement of one of its part. In fact, mechanisms are often used to transform movements of one kind into movements of another kind. For example, the crank-slider transform a rotational movement in a linear movement (see Figure 11). Another example is the pantograph which transforms the scale of a movement (see Figure 11). When using articulated objects, the user can control the action of the mechanism by moving one of its link. For example, when playing trombone, the user must control the position of the outer tube relative to the inner tube to adjust the tone.

One question of interest is whether people can judge the size of an element (link) of an articulated object from the movements of its parts. In the next chapter, which reports the results of a study on the bimanual perception of object size, we investigated one's ability to perceive haptically (without vision) the length of the links of large pliers by simply moving them. The plier is probably the simplest example of linkage with only two links and one internal degree-of-freedom that allows the two links to rotate around the revolute joint.

Another question of interest is whether the user can predict the movement of one part of the linkage when moving another part of the mechanism. As we have seen in a previous section, predictive control and forward models play a central role in current models of human motor control and haptic perception. One question that we investigated in the third chapter is whether seeing the mechanism can help predict the movement of one part of a linkage when moving another part.

Another difference between rigid bodies and articulated objects is that the dynamic properties of the linkages which changes with the linkage configuration. For example, the inertia tensor of a rigid body is invariant because it does not change shape. In contrast, the spatial distribution of the masses of a linkage and thus its apparent mass will change with its configuration. Another properties of linkage is to transmit forces and this transmission is also affected by the geometry and configuration of the linkage. The last part of this thesis addresses these issues.

1.6 Thesis outlines

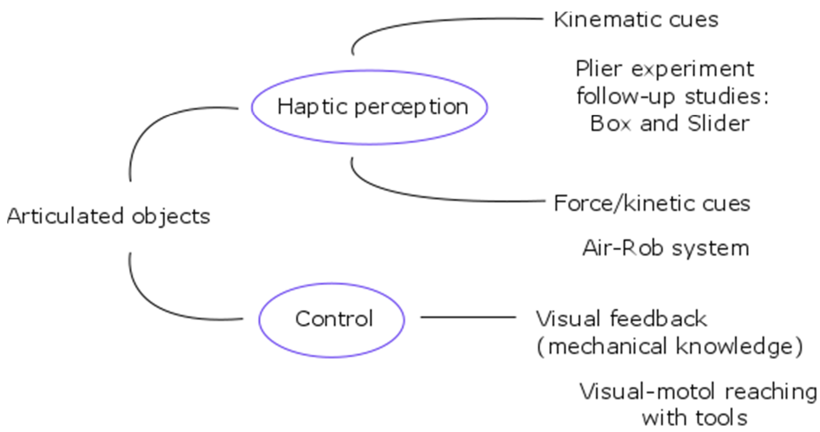


Figure 12. Outline of the thesis

Figure 12 illustrates the work done during thesis, which aimed at understanding better some aspects of the human capacity to perceive haptically the kinematic and dynamic properties of articulated objects as well as the human capacity to control them. In particular, this thesis includes studies that investigated the role of the two hands in the haptic perception of the size of large pliers, and the utility of seeing the mechanism to control the movement of the end-effector. In addition, we also developed a novel robotic device to perform experiments on the haptic perception of the interaction forces generated by the device.

Besides this introductory chapter, the thesis includes four other Chapters:

Chapter 2 investigates factors that influences the perception of the size of large pliers, held with both hands. In particular, it investigates the integration of information from the two hands when judging the size of the pliers and the influence of lifting the object on bimanual integration. This study includes additional experiments with wooden boxes and actuated apparatus with two movable flat surfaces. This study revealed that free manipulation is a factor that promotes bimanual integration by telling the brain that both hands are touching the same object. This Chapter includes a discussion on the place of bimanual integration in current accounts of multisensory integration. A preliminary report was published in World Haptics 2017 international conference, and a full article based on this Chapter has been submitted to Journal of Experimental Psychology: Human Performance and Perception.

Chapter 3 focuses on the influence of visual feedback on the reaching task with tools. It extends previous studies on visuo-motor control tasks with relatively complex tools. The experiments involve six types of 2-degree-of-freedom articulated mechanisms with prismatic and/or revolute joints, and introduce three visual representation conditions, with visual, pre-visual and non-visual feedback. These experiments showed that seeing the mechanism can help to control the movement of the end-effector, which indicate that people must have some internal model of the mechanism(s), which can be used to predict its motion.

Chapter 4 describes the development of AirRob, a novel device that was designed to study the perception of dynamic properties of articulated system. The initial concept was to design a low-friction, planar and modular system with variable link length and masses actuated by motors directly placed at the joints. The second part of the Chapter reports the results of a preliminary experiment that was carried out to understand how people interpret some force fields produced by the device.

Chapter 5 concludes the thesis with general discussion and possible future work.

Chapter 2

Study one

This study investigate the haptic perception of the size of hand-held pliers, a specific instance of articulated object made of two links attached by a revolute joint. In an initial experiment (Xu & Baud-Bovy, 2017; see Annex A), we measured precision with which people can judge the size of large pliers by simply opening and closing them and the contribution of each hand to this process. We compared performance in unimanual and bimanual conditions, with the pliers that could be fixed (grounded condition) or free to move. The chapter is actually focused a series of follow-up studies on object size perception and bimanual integration with different types of objects, including wooden boxes, an actuated apparatus with two movable flat surfaces and another experiment with large-size pliers, in uni-manual, bimanual grounded and bimanual free conditions. This chapter is the basis of an paper submitted at Journal of Experimental Psychology: Human Performance and Perception (Xu, Risso & Baud-Bovy, submitted). It is followed by a short appendix (Appendix A) that extend some discussions that were not included in the paper.

2.1 Background

Multiple sensory systems provide information about the environment. The brain must continuously process and organize this information, selecting and possibly merging it in a coherent whole. This work focuses on the integration of information coming from two hands holding an object in the absence of vision. While many studies have explored how information from different sensory modalities is combined or merged, fewer studies have investigated how different cues are integrated within the same modality, specifically the haptic modality. The goal of our study was to investigate whether information from the two hands is integrated when subjects estimate the size of an object with both hands. In the following, we start by reviewing previous work on multi-sensory integration in order to introduce the theoretical issues, which are the same whether the information comes from one or more sensory modalities. In particular, understanding how the brain deals with potentially conflictual information and/or when it decides to merge it together are long-standing research questions. We then review the literature on bimanual integration and introduce the objectives of our study.

2.1.1 Early work on multi-modal integration

Early research on multi modal sensory integration focused on situations where there was a conflict between pieces of information provided by different sensory modalities. A classic illustration is "ventriloquism", where the words pronounced by the puppeteer appear to come from the mouth of the puppet in conflict with the audio cues about the sound source (Vroomen, Bertelson, & De Gelder, 2001). Initial findings led to the view that the brain might accommodate such a conflict by simply ignoring one of the two sensory modalities (the stimulus or modality dominance hypothesis). In the case of a conflict between the visual and audio or proprioceptive modality, it was initially suggested that the visual modality dominates (Rock & Victor, 1964), but successive studies revealed a residual influence of the other modalities (Hershberger & Misceo, 1996; McDonnell & Duffett, 1972). This research line revealed that the direction and strength of the inter-sensory bias toward one or the other sensory modality depended on a variety of factors. In a review of this literature, Welch and Warren (1980) discussed evidence that the direction of the intersensory bias might depend on directed attention and/or on the accuracy or appropriateness of each modality. They also propose that the magnitude of the bias depends on the observers' assumption that they are in the presence of a single distal object (the *unity assumption*) and that the strength of this assumption is also a function of the number of physical properties (e.g., shape, size motion) that are redundantly represented in the stimulus situation (Welch, 1999). When the sensory signals are thought to refer to different objects or events, there would be no inter-sensory conflict and thus no inter-sensory bias.

2.1.2 Optimal (Bayesian) integration

These early observations have since been reinterpreted in light of optimal and Bayesian integration principles, a mathematical framework that allows one to define the best estimate that can be obtained by combining redundant information (Ernst & Banks, 2002). In brief, the optimal integration hypothesis prescribes that the best estimate s_{12} corresponds to a weighted average between the two sensory cues s_1 and s_2

$$s_{12} = w_1 s_1 + w_2 s_2 \tag{1}$$

where the weights w_1 and w_2 ($w_1 + w_2 = 1$) are proportional to the reliability of the stimulus:

$$w_1 = \frac{R_1}{R_1+R_2} \quad w_2 = \frac{R_2}{R_1+R_2} \tag{2}$$

and the reliability $R_i = 1/\sigma_i^2$ is simply the inverse of the noise (variance) of the corresponding cue. Assuming that the information provided by each cue is independent and normally distributed, it can be shown that the optimal (or Maximum Likelihood) estimate s_{12} that combines the two cues has a variance:

$$\sigma_{12}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \tag{3}$$

which is not only lower than that of the single cues but the lowest possible given the noise associated with each cue. This noise can be determined in behavioural experiments measuring the discrimination thresholds. A consequence of this framework is that, in the presence of a conflict, the bimodal estimate should be biased toward the most reliable sense, and many past observations have been reinterpreted accordingly. In addition, it is also generally held that the two cues are merged together before a decision is made (Ernst & Bülthoff, 2004).

More recently, Bayesian models have been extended to also address the question of when the brain should integrate information. For example, Körding et al. (2007) include the likelihood of two co-occurring signals having a "common cause" in their modelling of causal inference processes. Similarly, Ernst proposed reformulating the problem of integration in terms of a “coupling prior” representing the priori relation between the sensory signals (Ernst, 2007).

2.1.3 The haptic sense and sensory integration within a sensory modality

The haptic sense provides important information to control movement as well as information about our physical environment, especially the objects that we manipulate (Johansson & Flanagan, 2009). By definition, the haptic sense combines proprioceptive inputs coming from muscles, tendons and joints and tactile inputs coming from mechanoreceptors in the skin. The haptic sense can provide information about an object's material properties (softness/roughness, texture, slipperiness, stickiness, etc.), dynamic or kinetic properties (weight, compliance) and geometric or spatial properties (shape, size, position and/or orientation). A general characteristic of the haptic sense is that haptic information is typically acquired sequentially and actively by moving one's hand over an object (James J. Gibson, 1962) and that different movements are used depending on the type of information that needs to be acquired (Susan J Lederman & Klatzky, 1987).

Previous research on the haptic perception of the size or shape of objects has identified various haptic cues that are particularly relevant for our study (Pont, Kappers, & Koenderink, 1997, 1999). First, the size or shape of the object might be derived from the movement of the hand over the object's surface. Second, touch also provides information about the orientation of the object's surface at the contact point (tangent plane). Finally, touch, especially finger pad deformation, might provide information about the local curvature at the contact point. In the literature, position, tangent plane and curvature are known 0^{th}, 1^{st}- and 2^{nd}-order cues (Pont et al., 1997). In addition to these geometric cues, previous research has shown that the tangential component of the interaction force might also influence the perceived shape of the object (Robles-De-La-Torre & Hayward, 2001; Drewing & Ernst, 2006). Finally, the size or shape of hand-held objects can also be inferred from kinetic cues such as their moment of inertia or static torque (Turvey et al. 1998).

As noted above, the principles of multimodal integration apply not only to cues from different sensory modalities but also to different but redundant cues within one sensory modality. For example, there are several studies in the haptic literature suggesting that redundant haptic cues might be weighed according to their reliability. In particular, previous research on curvature perception showed that the weight given to each cue might depend on the size of the object, with 0^{th}-order cues playing a major role for large objects, 1^{st}-order cues playing a major role for medium size objects and 2^{nd}-order cues for small objects (Wijntjes, Sato, & Hayward, 2009). Drewing and Ernst (2006) have also found that geometric and force cues are integrated optimally in a shape discrimination task.

2.1.4 Bimanual integration

In this study, we focus on the haptic perception of the size of an object held with both hands, and whether information from the two hands is integrated optimally. Squeri et al. (2012) investigated whether information from the two hands was integrated optimally in a curvature perception task, where a bilateral robot moved the observer's hand(s) passively along the arc of a circle. They found no significantly different performance in the bimanual conditions with respect to the unimanual conditions. Panday, Tiest and Kappers (2013) asked observers to discriminate the size of large cylinders, with a diameter that varied from 19 to 45 cm (Panday et al., 2013). The cylinders lay on a table and the side(s) was/were explored with one or both hands. Contrary to Squeri et al.’s (2012) experiment, they found better performance in the bimanual condition. However, in a control condition where the observers had to report the distance between two flat surfaces, they found no difference between the performances in the unimanual and bimanual conditions. To explain these results, Panday et al. (2013) proposed that 2^{nd}-order cues related to the deformation of the hand on the cylinder might be integrated but not 0^{th}-order cues related to the position of the hand in space. They hypothesized that 2^{nd}-order cues consistent with cylindrical shape would suggest to the observer that the hands were touching the same object while 0^{th}-order cues only would not be able to elicit this impression. They also attributed the absence of integration in Squeri et al. (2012) to the fact that participants experienced only 0^{th}-order position cues while the robot moved one or both of their hands along the curved trajectory. This conclusion is also in line with the results of Wong, Wilson, Kistemaker and Gribble's (2014) more recent study in which bimanual proprioceptive acuity was not found to be significantly better than the best unimanual performance.

2.1.5 Object Grounding and the Unity Assumption

The main objective of this study is to investigate factors that might contribute to bimanual integration. As reviewed above, previous studies on haptic bimanual perception tasks have given contrasting results and surprisingly weak evidence of bimanual integration despite the fact that many motor tasks involve both hands. The absence of integration also stands in contrast with the tight integration in the control of the two hands as demonstrated by the difficulty in accomplishing truly independent movements with only one hand (reviews in Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004; Swinnen & Wenderoth, 2004). A critical feature of previous studies on bimanual integration that might be relevant in this context is that they all involved grounded objects. In other words, the objects could not be moved and no force was transmitted between hands. In contrast, the position of the hand-held objects involved in bimanual tasks is typically not constrained. This is the case when holding a tray or driving for example. In this type of bimanual action, the movement of the hand-held object and the hand are usually coupled and the force applied by one hand to the object is transmitted to the other hand and vice-versa (internal force). The main objective of this study is to test whether bimanual integration is influenced by grounding. Specifically, we hypothesize that bimanual integration might be enhanced when the object is not grounded and thus free to move. The hypothesis is that the motion coupling and force transmitted between the two hands might be used by the brain as a sign that two hands are holding the same object (unity assumption), thus triggering or enhancing bimanual integration (Welch & Warren, 1980).

In the following, we report the results of three experiments that investigated whether information from the two hands is integrated when estimating the size of an object bimanually, and whether grounding an object had influence on bimanual integration. In the first experiment, the task was to judge the size of wooden boxes. A box could lie on the table (grounded condition) or be lifted with both hands (free condition). In the unimanual conditions, the box was centered on the body mid-line so that it was possible to determine its size by touching one side with one hand. In the second experiment, we used an actuated apparatus with two movable flat surfaces, which resembled the grounded setup used by Panday et al. (2013). Finally, in the third experiment, we used large-size pliers and asked the participant to judge their size by opening and closing them. In the bimanual conditions, the fulcrum of the pliers could be fixed (grounded condition) or free to move. Our results show that grounding the manipulated object has an effect on bimanual integration, but it is not a necessary condition. With familiar objects such as wooden boxes, bimanual integration might also occur in the grounded condition. This is not the case, however, for less familiar objects such as the actuated apparatus used in the second experiment or the relatively complex tools used in the third experiment.

2.2 Experiment 1: box size discrimination

2.2.1 Methods

Participants. Nineteen participants, nine women and ten men (mean age 26.47 ± 3.89 years), participated in the experiment. All participants were right-handed except for one. None of the participants reported any known hand or neuromuscular disorder. All participants were naïve as to the goal of the experiment and had no previous experience with the task. One participant was excluded from the data analysis because he did not perform the task well enough to estimate the sensory threshold. The experiment was approved by the Ethics Committee of the Region of Liguria, and conducted according to the ethical principles defined by the Helsinki Declaration. All participants gave their informed consent before the experiment.

Apparatus and stimuli. Stimuli consisted in nine equally weighted wooden boxes sized 30 cm x 30 cm x (Variable Length) ranging from 32 to 48 cm by 2-cm steps. The 40 cm length box was used as the standard stimulus, while other boxes were used as comparison stimuli. All boxes were built to have the same weight (1413 ± 30 gr) and centre of mass (Figure 13).

Figure 13. The figure represents a blindfolded participant haptically interacting with a wooden box in the four experimental conditions. The top panels show the bimanual grounded (left) and free (right) conditions. In the bimanual free condition, the participant lifted the box a few centimeters above the table. The bottom panels represent the unimanual condition.

Experimental procedure and task. Participants were blindfolded before entering the experimental room so that they would not see the stimuli at any time. In the experimental room, the participants sat on a fixed chair with their bodies at 20 cm from the edge of a table. Before each experimental session participants were asked to point exactly in front of their body mid-line at least three times with arms extended and hands joined. The average position was marked on the table and used to centre the boxes during their presentation.

The task was a size-discrimination two-alternative-forced-choice task. During each trial, participants felt the size of two boxes in succession and at the end of the trial reported verbally which one was the largest.

The experiments included four conditions. In the unimanual conditions, each participant had to touch the side surface of the box with the left or right hand. In these conditions, he/she was asked to focus on the distance between the touched side of the box and the body mid-line. In the bimanual grounded condition, the experimenter maintained the box throughout the presentation to avoid movement while the participant touched the two lateral surfaces of the boxes with both hands for up to 5 seconds. In the bimanual free condition, the participant lifted the box a few centimetres, then put it back to its initial position. In both bimanual conditions, participants were asked to focus on the size of the box. Before the beginning of the experiment, the participants practiced the task in each condition until they felt comfortable.

Each trial included the presentation of the standard stimulus (40 cm) and one of the eight comparison stimuli. The order of presentation of the comparison and standard stimuli was randomized. Each comparison stimulus was presented seven times in each condition (method of the constant stimuli (Fechner, 1860), yielding a total of 224 trials. The experiment included seven blocks of 32 trials, which were subdivided into four sub-blocks of eight trials. Each sub-block corresponded to a condition and included all comparison stimuli in a random order. The order of presentation of the different conditions inside each block was randomized as well. The total duration of the experiment was 90-120 minutes per participant, divided into two sessions.

2.2.2 Data Analysis

For each participant and condition, a cumulative normal probability distribution was fitted to the responses using maximum likelihood estimation to obtain a psychometric function representing the probability of judging the comparison stimulus as larger than the standard stimulus. For each psychometric curve, we computed the point of equality (PSE), i.e. the box size perceived as larger than the standard distance in 50% of the trials, and the discrimination threshold (or discrimination limen, DL), which corresponded to the difference between the PSE and the box size perceived to be larger than the standard in 75% of the trials.

To statistically test an effect of the exploration condition, we performed a non-parametric Friedman test for repeated measures on the discrimination thresholds and PSE of unimanual and bimanual conditions. Whenever an effect was found, we tested the difference between conditions with two-tailed paired Wilcoxon signed-rank tests. To test whether integration took place, we computed the bimanual threshold predicted by optimal integration principles (Maximum Likelihood Estimation) for each participant. We tested whether the observed bimanual discrimination thresholds were smaller than or equal to the predicted MLE thresholds with one-tailed paired Wilcoxon signed-rank tests. Finally, we also examined if individual bimanual thresholds corresponded to the predicted MLE thresholds. In particular, we used Pearson-product-moment correlation to test the relationship between the observed values and the MLE predictions. For all tests, the level of statistical significance was set at 5% (Error Type I $\alpha = 0.05$).

2.2.3 Results

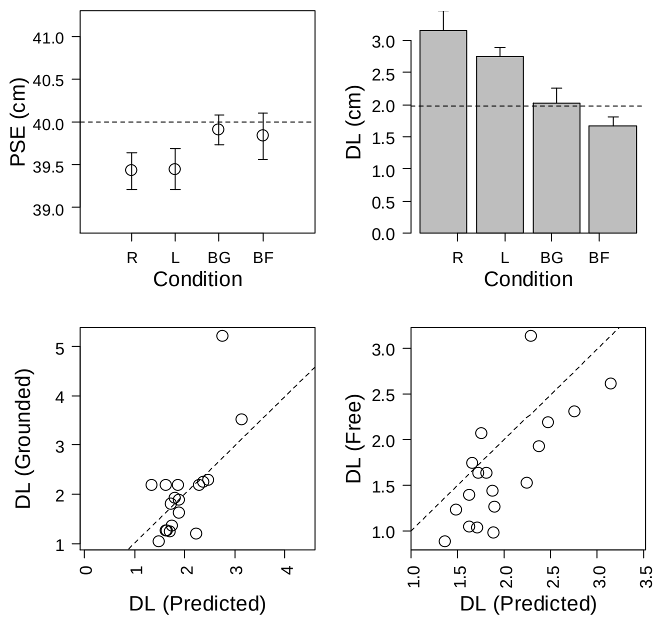


Figure 14. Results of the box size discrimination experiment. The top left panel represents the mean PSE (on the y-axis) for each condition (x-axis): Right (R), left (L), bimanual grounded (BG), and bimanual free (BF) condition. Vertical bars represent the standard error. The dotted line represents the standard box size (40 cm). The top right panel represents the mean discrimination thresholds (on the y-axis) for the four conditions (x-axis); the dotted line represents the predicted MLE threshold. The bottom panels show correlations between the individual discrimination thresholds predicted by MLE and those observed in the bimanual grounded condition (bottom left panel) or bimanual free condition (bottom right panel).

Figure 14. shows the mean haptic PSE (top left panel) and thresholds (top right panel) of the participants for the four experimental conditions. The differences between

the discrimination thresholds across conditions were statistically significant (Friedman test: $\chi^2(3) = 29.13$ $p<0.001$). In the unimanual conditions, the mean threshold was lower for the left hand (Mean ± SD: 2.75 ± 0.58 cm) than for the right hand (3.15±1.30 cm) even though the difference was not statistically significant; Wilcoxon test: V = 113, p = 0.246). As predicted by the optimal integration principles, the box size was estimated more precisely in the bimanual conditions than in the unimanual ones. Specifically, the unimanual DLs were higher than the bimanual grounded (2.03 ± 0.99) and free (1.66 ± 0.61) DLs. The Wilcoxon tests confirmed the statistical significance of the difference between unimanual and bimanual conditions (right hand vs grounded: V = 163, p < 0.001; right-hand versus free: V = 170, p<0.001; left hand versus grounded: V = 148, p = 0.005; left hand vs free: V = 170, p<0.001). The bimanual DLs did not differ from the MLE prediction (1.98 ± 0.47 cm) as confirmed by unilateral Wilcoxon tests (grounded vs MLE: V = 71, p = 0.739; free vs MLE: V = 25, p=0.997).

Although the differences were small and not statistically significant, several indices suggest that bimanual integration was stronger in the free condition than in the grounded one. First, the average bimanual threshold was lower in the free condition than in the grounded one (grounded: 2.03 ± 0.99; free: 1.66 ± 0.61) although the difference was not statistically significant (Wilcoxon test: V = 123, p=0.108). Second, at the individual level, 72% of participants had a lower threshold in the free condition than in the grounded condition (13 out of 18; binomial test: p=0.09). Finally, we also found a slightly stronger correlation between the discrimination thresholds predicted by optimal integration and in the free condition (r = 0.73, n = 18, p<0.001; see Figure 2, bottom right) than in the grounded condition (r = 0.70, n = 18, p = 0.001; see Figure 2, bottom left).

2.2.4 Discussion

The results of the experiment with boxes indicate that bimanual integration occurred in the grounded and free conditions. Some evidence indicates that bimanual integration was stronger in the free condition than in the grounded if one considers all results together but we did not find statistically significant differences between the two conditions, possibly because integration reached in the grounded condition was close to the maximum gain that can be theoretically achieved by integrating information from both hands. While we had expected to find bimanual integration in the free condition, this was not the case in the grounded condition. As a matter of fact, the results in the grounded condition are apparently in contrast with the results of an experiment in Panday and colleagues (2013), who did not find bimanual integration in a similar task where participants judged the distance between two flat surfaces. These results are also in contrast with the findings of Squeri et al. (2012) and Wong et al. (2014) who also found no clear evidence of bimanual integration in a curvature and position discrimination task, respectively.

Several factors might explain why bimanual integration might have occurred in the grounded condition in our experiment. First, it is important to note that our stimuli consisted of simple wooden boxes, which are very familiar objects in our everyday experience. Second, the grounded and free conditions were mixed together. As a result, the participants knew that they were touching boxes, i.e. a single object, even in the grounded conditions. Notably, all the participants reported that they immediately thought that the stimulus was a box. In this respect, it should be noted that the experimental setup in Panday et al. (2013) and Squeri et al. (2012) differed markedly from ours. In Squeri et al. (2012), the apparatus consisted in two robotic arms, each with a handle that the participant grasped and that moved the participant's hand(s) along the desired trajectory. In Panday et al. (2013), it consisted in two flat vertical surfaces mounted on a rail and connected by a steel thread that could be used to move their position symmetrically with respect to the centre of the rail. In their discussion, Panday et al. (2013) suggested that a reason why bimanual integration occurred with the curved surfaces but not with the flat surfaces in their study is that curvature could elicit a representation of the object shape in higher-order brain processes, where cues from both hands can be integrated, whereas position does not. They relate the lack of integration in Squeri et al. (2012) to the fact that the task did not require participants to form an opinion about the object being explored, but to simply compare curvature. The objective of the next experiment is to confirm the absence of bimanual integration when the experimental apparatus does not elicit the belief on the part of the participant that he/she is touching boxes. In a sense, the goal is to replicate the results of Panday et al. (2013). To that end, we used an actuated device, which could move two vertical metallic panels along a linear guide as the experimental setup.

2.3 Experiment 2: distance discrimination of flat surfaces

2.3.1 Methods

Participants. Twelve new participants (mean age 26.58 ± 2.54 years; five females and seven males) participated in the experiment, including ten right-handed, one left-handed and one ambidextrous person. None of the participants had participated in the first experiment; nor did they have or report any known hand or neuromuscular disorders. All participants gave their informed consent prior to testing.

Experimental procedure. The experimental setup was a linear guide (see Figure 15) with two actuated blocks that could move along a 51 cm long workspace. Two vertical flat surfaces (20 by 30 cm) were affixed onto the actuated blocks. A custom program adjusted the distance between the two plates during the experiment. The device was placed 10 cm from the edge of a table.

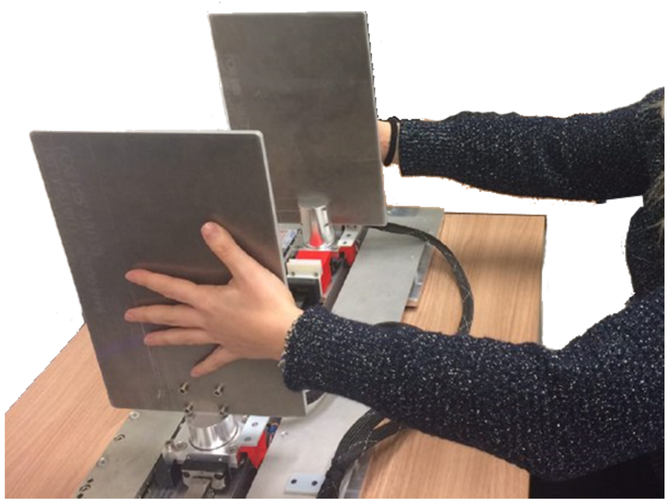


Figure 15. Discrimination of distance between flat surface experimental setup. Representation of a participant interacting with the setup in the bimanual condition. The experimental setup is a force feedback device with a long rectangular workspace (10.5 x 51.0 cm). The mechanical structure consisted of two vertical flat surfaces powered by two motors. During the haptic exploration of the stimulus, the participant was blindfolded and wore a headset playing white noise in order to supress any additional auditory cue given by the sliding of the panels.

The task and experimental procedure was the same as in Experiment 1. Each participant sat 20 cm from the table on a fixed chair with their body 20 cm from the edge of the table. Participants were blindfolded and wore a headset playing white noise to suppress audio cues.

The experiment included two unimanual conditions (right and left hand) and one bimanual condition. In the unimanual conditions, participants were instructed to focus on the distance between the flat panel and the mid-line of their body. In the bimanual condition, participants were instructed to focus on the distance between their two hands.

Each trial involved the successive presentation of the standard stimulus (27 cm distance) and a comparison stimulus (one of ten possible distances ranging from 22 to 32 cm by 1-cm steps, excluding the 27 cm distance). Both stimuli were centred on the body midline, which was identified with the same procedure as in the first experiment. The administration order of the standard and comparison stimuli was randomized.

The whole experiment included seven blocks of 30 trials, yielding a total of 210 trials. Each block was divided into three sub-blocks of 10 trials, where all comparison stimuli were presented in the same condition. The order of presentation of the different stimuli inside each sub-block, and conditions inside each block were randomized. The total duration of the experiment was 50-60 minutes per participant, divided into two sessions.

Data were analysed in the same way as in Experiment 1.

2.3.2 Results

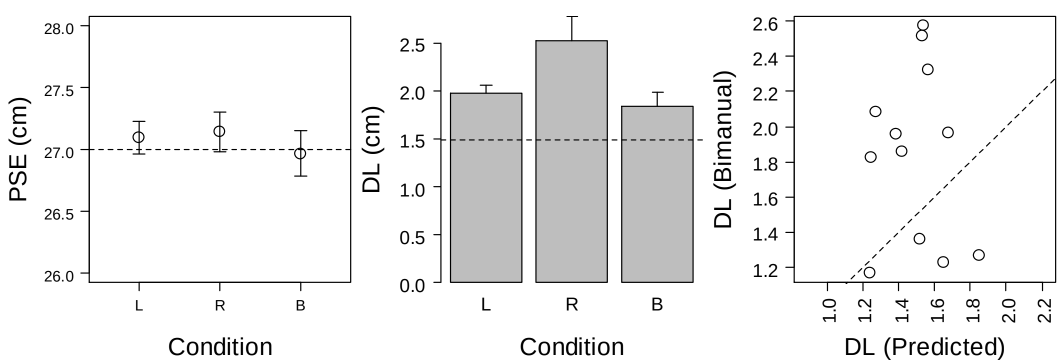


Figure 16. Results of the distance discrimination experiment with flat surfaces. Left panel: Mean PSEs (y-axis) for each condition (x-axis): right (R), left (L) and bimanual (B) conditions. The dotted line represents the distance of the standard (27 cm). Middle panel: Representation of the mean discrimination thresholds (on the y-axis) for the four conditions (x-axis). The dotted line represents the predicted MLE threshold. Vertical bars represent the standard error. Right panel: Correlations between the individual discrimination threshold predicted by MLE (x-axis) and the bimanual condition (y-axis).

Figure 16 shows the PSE (left panel) and DLs (middle panel) for the three experimental conditions. The differences between discrimination thresholds across experimental conditions were barely statistically significant (Friedman test: $\chi^2(2) = 6.17$, $p=0.046$). The discrimination performance was slightly better with the left hand (mean ± SD: 1.97 ± 0.2 cm) than the right hand (2.51 ± 0.88 cm; Wilcoxon test: $V = 64$, $p = 0.052$).

The discrimination performance with both hands (1.84 ± 0.49 cm) was also better than the right hand (Wilcoxon test: $V = 67$, $p = 0.027$) but did not differ significantly from the left hand (Wilcoxon test: $V = 46$, $p = 0.622$). Importantly, the threshold in the bimanual condition was also above what was predicted by optimal integration (1.49 ± 0.18 cm; one-tailed Wilcoxon test: $V = 63$, $p = 0.032$). Further, the predicted and observed bimanual thresholds were not shown to be significantly correlated at the individual level ($r = -0.09$, $n = 12$, $p = 0.784$; see Fig. 16, right panel).

2.3.3 Discussion

As in the first experiment and in Panday et al. (2013), we found a slight advantage for the left hand with respect to the right hand in the unimanual condition. At the individual level, 83 % of individuals in this experiment and 61% of the participants in the box experiment performed better with the left hand than the right, which is statistically significant (21 out of 30; two-tailed binomial test: $p = 0.043$). It is noteworthy that Wong et al. (2014) found that a similar percentage of participants (59%) had the best acuity with the left hand in their position discrimination task. Altogether, the results of the unimanual conditions suggest a small laterality effect in this task.

The pattern of results with respect to bimanual integration is clearly different from Experiment 1. The discrimination performance in the bimanual condition was similar to the best unimanual performance and worse than the MLE prediction, which denotes a lack of integration in this experiment. In this respect, it should be noted that the aforementioned difference between the two unimanual conditions is small enough so that integrating information from the less performing hand might still bring an advantage in the bimanual condition as shown by the statistically significant difference between the MLE prediction and the best hand. The correlation between the actual and the predicted threshold in the bimodal condition was close to zero and not statistically significant. It is unlikely that the difference in the size of the stimuli between this (27 cm standard) and the first (40 cm standard) experiment can explain the difference between the two experiments. Indeed, Panday et al. (2013) did not find evidence of bimanual integration at any distance, with standards that ranged from 19 to 45 cm. The difference between the two experiments is most likely due to the experimental setup, which was similar to the one used by Panday et al. (2013). Moreover, the fact that none of the participants in this experiment reported having the impression of holding a box or a single object is also in line with the idea that bimanual integration might require the assumption that both hands are touching the same object (see General Discussion).

The results of the first experiment suggest that bimanual integration can happen with grounded objects, as long as they are familiar and they evoke the idea that both hands are holding the same object. Bimanual integration also appears to be reinforced in the lifted condition but the difference between the two conditions was minimal. In the following experiment, we consider bimanual integration when handling objects – large hand-held pliers - that are less familiar than boxes. The hypothesis is that less integration will occur in the grounded condition than in the bimanual free condition because the lack of familiarity with the objects would make it more difficult to process information at a higher level whereas there can be no doubt that one's two hands are holding a single object when lifting it.

2.4 Experiment 3: Plier size discrimination

The plier study involved three groups of participants who performed the same task with small methodological differences. The results of the two first groups are analysed together here for simplicity. The experiment with the third group can be viewed as a replication and confirmation of the results obtained with the two first groups of participants.

2.4.1 Methods

Participants. The first group included 18 participants (ten females and eight males, aged 28.1 ± 6.7 years). The second group included 20 participants (seven females and thirteen males, aged 29.7 ± 9.9 years), including nine participants from the first group. All participants were right-handed. The 12 participants of the third group were all naïve with respect to the experimental task and included six males and six females, aged 30.6 ±6.5 years, 11 right-handed and 1 left-handed. None of the participants reported any known hand or neurological deficits. The experimental protocol was approved by the Ethic Committee of the Region of Liguria, and all the participants gave their informed consent prior to the task.

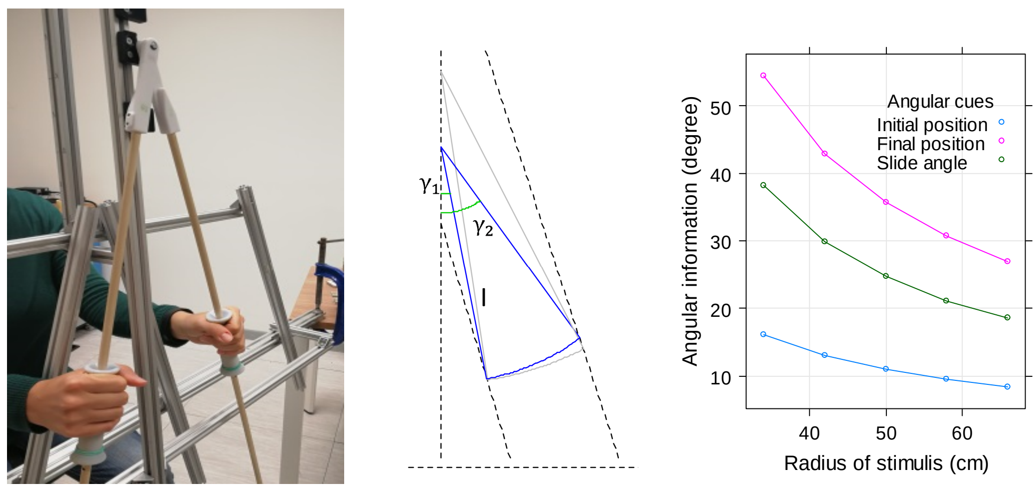


Figure 17. Plier size discrimination experimental conditions and stimulus properties. Left: Experimental conditions: (a) bimanual free motion (b) bimanual grounded (c) unimanual grounded conditions. Middle: Schematic representation of the motion of two different pliers in the grounded conditions. The dotted lines represent the frame, which limited the range of motion. The figure shows the angles between the vertical and the plier at the two extrema ($\gamma 1$ and $\gamma 2$) of the range of motion. Right: Relationship between the radius of curvature and other cues for plier discrimination (see text).

Apparatus. During the experiment, the participant sat in front of a metallic frame, which was used to limit the range of motion of the hand(s) and to fix the pliers' rotation axis when needed (see Figure 17). The pliers used in these experiments were formed by two wooden sticks (diameter = 10 mm, length=80 cm) connected by a revolute joint at one extremity. An ergonomically designed 3D printed handle was fixed on the wooden stick at a distance that varied for different pliers. The size of the plier is defined by the distance between the fulcrum and the position of the handle. All pliers had the same weight (0.128kg) to remove any possible kinetic cues that could be used to discriminate between pliers during their manipulation.

Table 1. Summary of experimental conditions for the three groups

	Comparison stimuli length (cm)	**Training**	**Condition order**
1st group	{36, 43, 50, 57, 64}	No	Blocked, counter-balanced across subjects
2nd group		Yes	
3rd group	{34, 42, 47, 53, 58, 66}	Yes	Mixed within subjects

For all groups, the distance between the revolute joint and the handle was fixed at 50 cm for the standard stimulus. For the comparison stimuli, this distance varied from 36 to 64 cm (36, 43, 50, 57, 64 cm) for the first two groups. For the third group, the distance between the fulcrum and the handle of the comparison stimuli varied from 34 to 66 cm (34, 42, 47, 53, 58, 66), as shown in Table 1.

Task and experimental conditions. The task was a size-discrimination two-alternative-forced-choice task. For each trial, the experimenter put the standard and a comparison plier successively in the participant's hands. The participants were required to hold the plier with a power grasp. A groove on the handle constrained the index finger position to fix the hand positions on the handles. Participants were instructed to open and close each plier three times. The hand movement range was limited by the metallic frame, which was fixed on the table (see Figure 17). At the end of the trial, the subjects had to report which one of the two pliers they perceived was the longest.

The experiment included three conditions: the bimanual free condition, the bimanual grounded condition, and the unimanual grounded condition. In the unimanual and bimanual grounded conditions, the rotation axis of the pliers was fixed to the metallic frame. The height of the rotation axis was adjusted as a function of the size of the pliers, so as to keep the initial hand position at the same height. In the unimanual condition, the right hand was used to hold the right link of the plier. In the bimanual conditions, the participants grasped the plier with two hands. In the bimanual free condition, the movement of the plier fulcrum was only partially constrained. In the first and second experiments, the revolute joint of the fulcrum was free to move only in the vertical direction due to a peg aligned with the fulcrum inserted into the sliding rail of the metal structure. In the third experiment, the plier was free to move in the fronto-praralle plane but still prevented from moving outside this plane by the metallic structure, thus eliminating possible kinetic cues such as static torque about the plier size.

The method of constant stimuli was used in all the experiments. For the first two groups, the three experimental conditions were completed one after another, in an order that was counterbalanced across participants. Each condition was divided in blocks of five trials that corresponded to the presentation of all comparison stimuli in a random order. Each comparison stimulus was presented 10 times in each condition, yielding a total of 150 trials. For the third group, the experimental conditions changed after a block of 6 trials, which included all possible comparison stimuli in a random order. The condition corresponding to the first block and the order of the experimental conditions in the following blocks was counterbalanced across subjects. The experiment for this group included 8 blocks of 6 trials for each condition, yielding a total of 144 trials. The experiments took about 1.5 to 2 hours for each subject to complete.

Training procedure. The participants in the first group were given instructions about the task, including a drawing of two differently-sized pliers. Then they were blindfolded before the beginning of the experiment to prevent them from seeing the pliers. No feedback about their responses was given during the experiment. Because several subjects in the first group had difficulties in understanding the task, the second and third groups received a training session to familiarize them with the task and stimuli before the beginning of the experiment. First, the participants were shown the pliers and could manipulate them before being blindfolded. Second, the participants were given two blocks of practice trials including all the comparison stimuli before starting the experiment. Moreover, feedback about the correctness of their responses was given during the practise trials. If the participants had responded erroneously during a practice trial, they were given back the two pliers so that they could manipulate them for a second time. No feedback was given during the rest of the experiment.

Cues in plier size perception. Various cues might give information about the length of the pliers. Geometrically, the pliers' size corresponds to the radius of curve of the circle defined by the movement of the handle around the revolute joint (instantaneous center of rotation). In the grounded condition, the center of rotation is fixed and the task amounts to discriminate the curvature of the circle defined by the handle motion. As noted in the introduction, haptic cues about curvature or shape can be classified into position (0^{th}-order) cues, tangent plane (1^{st}-order) cues and local curvature (2^{nd}-order) cues (Pont et al., 1997). In this task, proprioception provided information about hand position (0^{th}-order cue) and about orientation of the handle (1^{st}-order cue) but local curvature (2^{nd}-order) cue were absent.

The *local attitude* corresponds to the angle between the plier and the tangential vertical plane. The limits of movement restricted by the mental frame define a circular sector, whose arc corresponds to the *slide angle* ($\gamma_s = \gamma_2 - \gamma_1$), i.e. to the difference between the local attitude at the initial (γ_1) and final (γ_2) positions. As noted above, the position of the center of rotation was adjusted so that the initial hand position would be the same for all plier sizes in the grounded condition. The difference in height between the two ends of the motion curvature is termed, unsurprisingly, as *difference-in-height* (*h*). Over the range of motion allowed by the setup, the relationship between the pliers' size and angular cues are approximatively linear (see Figure 5).

2.4.2 Data analysis

The participants' responses were fitted with a cumulative normal probability distribution using maximum likelihood estimation to obtain a psychometric function as in Experiments 1 and 2. For each participant and condition, we computed the PSE and 75% discrimination threshold (DL). To estimate variability in a robust manner, we used the Median Absolute Deviation (MAD) scaled to yield an estimate of the standard error. We excluded participants who had a negative or a very large discrimination threshold in one of the conditions. The exclusion criterion (DL>24 cm) was identified visually to include the main lobe of the threshold distribution. It also corresponds to choosing the median + 3*MAD = 23.6 cm. We used the same non-parametric statistical methods as in Experiments 1 and 2 to analyse the effect of the condition and to test for bimanual integration.

2.4.3 Results

For the first group, 9 (50%) participants had a large (DL > 24) or negative discrimination threshold in one of the conditions. A close look at the data showed that the worst performance typically happened at the beginning of the experiment. For this reason, we introduced a training phase before starting the experiment with the other groups. For the second group, only three participants (15%) had a negative or large threshold in one of the conditions. For simplicity, data from the first and second groups (Groups 1&2) are analysed together (see Xu and Baud-Bovy, 2017 for a separate analyses). For the participants in the second group who were already part of the first group and performed well twice (N=5), we retained only the second performance to avoid issues with repeated-measures analyses, yielding a total of 21 unique participants for Groups 1 & 2. The results are similar if the analyses are conducted only with the well-performing participants of the second group (N = 17). All the participants in the third group performed the task well.

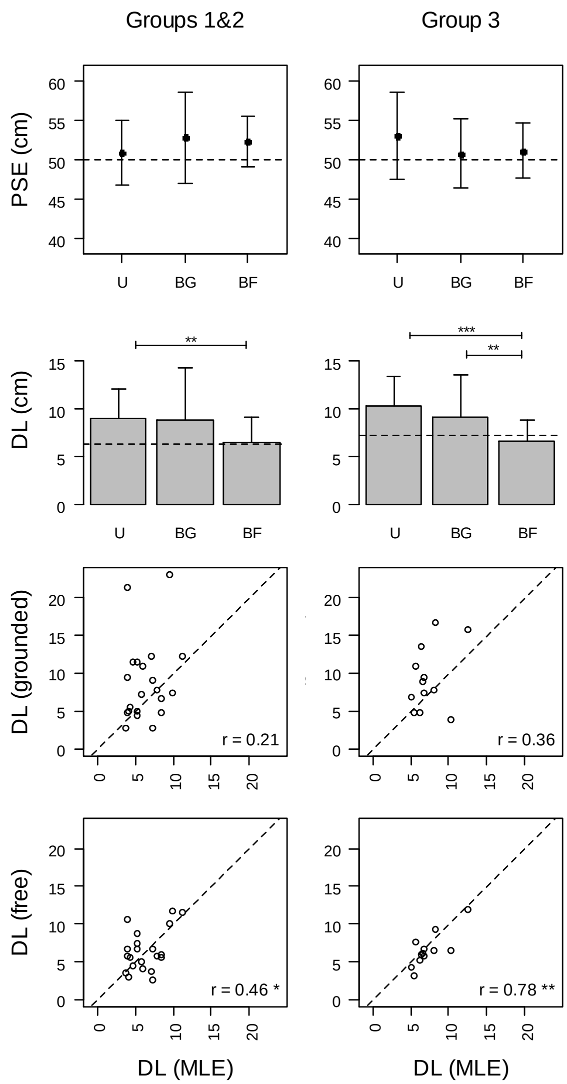


Figure 18. Results of the plier size discrimination experiment. The first column presents the results from Group 1&2, and the results from Group 3 is presented in the second column. First row: Average PSE in unimanual (U) and bimanual grounded (BG) and

bimanual free (BF) conditions. The horizontal dashed line represents the standard (50 cm) stimulus. Vertical bars represent the standard error. Second row: Average discrimination threshold. The MLE column represents the predicted discrimination threshold. Third row: Comparison between individual thresholds predicted by MLE and observed ones in the bimanual grounded condition. Last row: Comparison between individual thresholds predicted by MLE and observed ones in the bimanual free condition. ***: $p<0.001$; **: $p<0.01$; *: $p<0.05$.

For the first two groups, the average (±SD) discrimination thresholds were 8.9 ± 3.2, 8.8 ± 5.4 and 6.4 ± 2.7 cm for the unimanual, bimanual grounded and bimanual free condition respectively (see Figure 18). A non-parametric Friedman rank test on the discrimination thresholds showed a significant effect of the condition ($\chi^2(2) = 7.71$, $p = 0.021$), as shown in Figure 6. Paired two-tailed Wilcoxon signed-rank tests indicated a significant difference between the free bimanual condition and the unimanual condition ($V = 201$, $p = 0.002$), and between the free and grounded bimanual conditions ($V = 164$, $p = 0.096$). The difference between the grounded bimanual and the unimanual conditions was not statistically significant ($V = 135$, $p = 0.517$). There was no statistically significant effect of the condition on the PSE (Friedman $\chi^2(2) = 1.17$, $p = 0.56$; mean ± SD: 1.9 ± 4.3 cm).

Results from the third group confirmed the above. We found a significant effect of condition (Friedman rank test: $\chi^2(2) = 15.17$, $p < 0.001$) and significant differences between the unimanual and the free bimanual conditions (Wilcoxon test: $V = 78$, $p < 0.001$) and between the grounded and the free bimanual conditions ($V = 71$, $p = 0.009$), but not between the unimanual and grounded bimanual conditions ($V = 51$, $p = 0.380$).

Table 2. Thresholds expressed in four cues

Cues	Free	Grounded	Unimanual
Radius of curvature (cm)	6.59±2.25	9.22±4.27	10.33±3.10
Slide angle ($\gamma2 - \gamma1$, deg)	3.66±1.76	5.51±3.25	5.81±2.23
Angular attitude ($\gamma2$, deg)	5.12±2.42	7.65±4.43	8.15±3.10
Difference-in-height (h, cm)	1.18±0.57	1.77±1.03	1.90±0.73

Table 2 reports the mean discrimination thresholds in terms of the radius of curvature, slide angle, final angular attitude, and difference-in-height in the three exploration methods for the third group.

Assuming that the unimanal threshold DL_u is the same for both hands, Maximum Likelihood Estimation (MLE) predicts that the bimanual threshold should correspond to $DL_b = DL_u/\sqrt{2}$ (see eq. 1). For both groups, the thresholds predicted by MLE was not statistically different from the bimanual threshold in the free conditions (one-tailed Wilcoxon test for the first & second group: V = 116, p = 0.500; for the third group: V = 18, p = 0.954). The threshold in the grounded was larger than the MLE for all groups but the difference was only marginally significant only for the third group (one-tailed Wilcoxon test for the first and second groups: V=167, p=0.038; for the third group: V = 60, p = 0.055). We also found that the predicted (MLE) thresholds were better correlated with the thresholds measured in the free condition (Pearson coefficient of correlation for groups 1&2: r = 0.456, p = 0.038; group 3: r = 0.782, p = 0.003) than those observed in the grounded condition (groups 1&2: r = 0.209, p = 0.363; group 3: r = 0.362, p = 0.248).

2.4.4 Discussion

Our results show that people can discriminate the length of hand-held pliers by simply opening and closing them, given an opportunity to familiarize themselves with the pliers and the task. While about 50% of the participants had difficulty performing the task in one of the conditions, we found a much smaller proportion of such participants in the second group (15%) and none in the third group. For the first two groups where the order of presentation conditions was blocked and counterbalanced across participants, poor performance typically occurred in the first condition (see Xu & Baud-Bovy, 2017 for a preliminary report including a separate analysis of the first two groups). Introducing a brief training period and showing the pliers to the subjects when explaining the task allowed almost all participants to perform it from the onset in the second experiment. In addition, mixing the order of presentation of the condition in the third experiment resolved this issue.

For all groups, we found a marked difference between the bimanual free and the bimanual grounded performances, and almost no difference between the unimanual and the bimanual grounded performances. In the free condition, the performance corresponded to the optimal integration or MLE prediction. At the individual levels, we also found a good correlation between the MLE prediction and the performance in the free condition. The experiment with the third group confirmed the results obtained with the two first groups. It showed a particularly strong correlation between individual bimanual thresholds in the free condition and corresponding bimanual thresholds predicted by optimal integration, as well as a much weaker correlation in the grounded condition.

It is important to note that the free condition did not provide more cues about the pliers' size than the bimanual grounded condition. As a matter of fact, the absolute position of the hands cannot be a cue in the free condition since they are free to move in the frontal plane; the size of the plier or the radius of curvature must be inferred from the relative position and orientation of the two hands. In fact, the task in the grounded conditions is arguably easier because the motion is restricted to a unidimensional trajectory. Moreover, the plier size had a small but systematic effect on the final hand position (see Figure 5) despite the adjustment of the position of the rotation axis in the grounded condition to insure that the initial height of the handle would not vary with plier size.

We also took care to avoid possible additional kinetic cues in the free condition (Turvey et al., 1998; Turvey & Carello, 2011). For the first two groups, the motion of the pliers in the free condition was limited by fixing the joint in a sliding mechanism that allowed it to move in the vertical direction. For the third group, the motion of the plier was restricted to the fronto-parallel plane by the metallic frame. In either case, the center of mass of the pliers was above the hands and did not produce static torques. In addition, the lightness of the pliers, the fact that the pliers' links were all of the same size (only the hand position changed) and the relative slowness of the aperture movement essentially suppressed any possible inertial cues which might otherwise yield information about the length of hand-held sticks when they are wielded (Turvey et al., 1998).

Finally, it should be noted that the motion of the pliers and/or the force transmitted between the two hands does not provide additional cues about the pliers' size in the free condition. However, the physical interaction while subjects manipulated the pliers in the free condition provided information that their hands held the same physical object. In this respect, it is important to note that the presence of a single joint does not uncouple the hand movements completely. While the joint removes the transmission of (internal) torques between the two hands, linear forces are still transmitted. For example, the plier's vertical force produced by one hand is felt by the other hand, unless both hands move vertically together or the hand orientations change. In contrast, no force is transmitted between the two hands in the grounded condition where the position of the pliers' rotational fulcrum is fixed: the radial force component with respect to the revolute joint is transmitted to the structure holding the plier while the tangential force component yields a displacement of the stick without force transmission to the other hand. As a result, the two hands move completely independently.

In the grounded condition where the hand path corresponds to an arc of a circle, the task is akin to a curvature discrimination task. The value of the pliers' size discrimination thresholds in these conditions (~9 cm) are above the discrimination thresholds (~4 cm) found by Sanders and Kappers (2006) for a cylindrical stimulus with a radius of curvature of 40 cm. One reason for the difference might be that the exploration of the cylinders with the entire hand in Sanders and Kappers (2006) provided 2^{nd}-order cues, which are lacking in our experiment with pliers.

Altogether, the results of this experiment are in line with the hypothesis that grounding might influence bimanual integration. We also found bimanual integration was absent or much weaker in the grounded condition, which also included 1^{st}-order cues such as the slide angle. Therefore, the mere presence of additional angular information (slide angle or local attitude) is not a sufficient cause for integration to happen; the integration happens only in the free condition when the two hands interact physically and the pliers' position is not constrained. In this respect, it is interesting to note that the two hands did not interact physically in Squeri et al.'s (2012) study, where the trajectories were constrained by the robot, which moved the two hands passively. Our results also indicate that curvature information (2^{nd}-order cue) is not necessary for integration to happen.

2.5 General discussion

The first objective of this study was to find out whether our brains combine or integrate redundant information when estimating the size of an object with both hands. The second objective was to test the hypothesis that free manipulation enhanced bimanual integration. To that end, we manipulated the type of objects and the way of handling it in the bimanual conditions. With the wooden boxes, we found evidence that bimanual integration happened in both grounded and free conditions, with a slightly better performance in the free condition. In contrast, we did not find evidence of bimanual integration with the slider apparatus in the grounded condition. Finally, we did find evidence in the third experiment with large hand-held pliers that bimanual integration occurred in the free condition but not in the grounded ones.

2.5.1 Experimental factors that influence bimanual integration

Table 3. Summary of the principal experiments on bimanual integration.

Study	Task	Stimulus	Haptic cues (order)	Grounded/ Free	Bimanual integration
Squeri et al. 2012	Curvature	Passive movement along a curved path	0	Grounded	No
Panday et al. 2013	Object size	Curved surfaces compatible with a cylindrical shape (Exp. 1)	0, 1, 2	Grounded	Yes
		Separated flat surfaces (Exp. 2)	0, 1	Grounded	No
Wong et al. 2014	Position	Passive movement toward a position	0	Grounded	No
This study					
Exp. 1	Object size	Boxes	0, 1	Grounded Free	Yes Yes
Exp. 2	Object size	Separated flat surfaces	0, 1	Grounded	No
Exp. 3	Object size	Pliers	0, 1	Grounded Free	No Yes

Table 3 summarizes the results of the principal experiments on bimanual integration. As noted earlier, previous studies that have investigated bimanual integration in tasks comparable to ours have found little evidence of bimanual integration. A curvature discrimination task where a bimanual planar manipulandum moved the hand(s) along a curved trajectory, Squeri et al. (2012) did not find evidence for bimanual integration. Nor did Panday et al. (2013) find evidence for bimanual integration in an object size discrimination task when participants had to judge the distance between two flat panels placed symmetrically with respect to the body midline (Exp 2). We found the same result in the second experiment where we used a setup similar to that used by Panday et al. (2013). However, Panday et al. (2013) found evidence for bimanual integration when the flat surfaces were replaced by curved surfaces (Exp 1). To explain this result, Panday et al. proposed that small changes in the task and experimental situation between the two studies might have led the participant to process sensory information at a higher level, where shape is represented and cues from both hands might be integrated. In their experiment, the radius of curvature and the distance between the two curved surfaces corresponded to that of a large cylinder. Moreover, participants were encouraged to imagine a circular cylinder when touching the surfaces. In contrast, the participants did not feel the curvature of the surface (2^{nd}-order cues) in Squeri et al. (2012) since they were holding a handle, which provided only position information (a 0^{th}-order cue). This conclusion is in line with the results of a more recent study, which investigated whether holding a position with two hands would improve the encoding of the position (Wong et al., 2014). In this study, a robotic manipulandum moved the hand(s) at a reference position on the body mid-line and successively to a test position on the left or right side of the reference position after a distracted movement. Results indicated that the position discrimination threshold in the bimanual condition was worse than the threshold predicted by the optimal integration model.

The results with the boxes confirm that bimanual integration can happen with grounded and flat objects and show that curved surfaces (2^{nd}-order cues) are not necessary for bimanual integration to happen. To explain the difference between the results of the first (boxes) and second (vertical plates) experiment, it is important to note that the grounded and free conditions were mixed in the experiment with boxes. As discussed in detail below, the free condition provides unequivocal evidence that the hands are holding the same object. Although integration happened in the grounded condition as well, the context might have indicated that both hands were holding the same object, leading presumably to a higher-level representation of the sensory signals where information from each hand would be integrated as suggested by Panday et al. (2013). In this respect, it is also noteworthy that all subjects – without ever seeing the experimental setup - reported holding boxes in the first experiment, which never happened in the second experiment where we used the robotic manipulandum.

As hypothesized in the introduction, we also found that bimanual integration occurred when the boxes were lifted. The effect that lifting the boxes had on bimanual integration was however only marginally stronger in the free condition, which might simply reflect the fact that integration can only improve discrimination performance up to a given point, which was essentially achieved in the grounded condition.

The difference between the grounded and the free conditions was largest in the third experiment, which involved large hand-held pliers. It should be noted that the participants knew that they were holding pliers in this experiment. They were shown the pliers and told that the length of the sticks was the same in the bimanual condition. Moreover, the second and third group performed familiarization trials to insure that the task was performed correctly before starting the experiment. Despite all this information, we did not observe bimanual integration in the grounded condition, even for the third group of participants, who experienced the free and grounded condition in a mixed order. These results show knowledge alone of holding an object might not suffice for integration to occur, in particular with an object that might not be very familiar like a plier. Although this task in the grounded condition is akin to a curvature discrimination task, the experimental situation differed from Panday et al.'s (2013) first experiment. The pliers lack the curvature cue presented in Panday et al.'s (2013) experiment with curved surfaces. Moreover, the instructions and position of the hands on each side of the (imagined) cylinder might have favoured bimanual integration in Panday et al. 's (2013) experiment.

The bimanual grounded integration observed in the free condition with the plier cannot be explained by the presence of additional cues in the free condition (see Discussion of Exp. 3). We hypothesize that the pattern of force and hand movement when manipulating an object bimanually without constraints is a strong indicator that the two hands are holding the same object. Interestingly, this factor appears stronger than knowing that one holds one object as demonstrated by the lack of integration with holding pliers in the grounded condition. It would be interesting in the future to know whether the mere knowledge that one is holding a box without actually ever lifting it would be sufficient to trigger bimanual integration.

While these results might appear confusing at first glance, previous studies on sensory integration have clearly established that many factors affect this integration process. In fact, we believe that our results fit the emerging viewpoint on multi-sensory integration well. We discuss this in the next section.

2.5.2 Bimanual integration in current accounts of sensory integration

The goal of sensory integration is to obtain a more reliable signal by fusing together redundant but noisy information. Maximum Likelihood Estimation and Bayesian theory provide a basis to derive a quantitative prediction about the best possible performance that can be achieved under these conditions. As noted in the introduction, a major problem that the brain (or our perceptual system) must solve is to decide *when* to integrate sensory information, which makes sense only if the information is redundant (Ernst & Bülthoff, 2004). A related question is *how* the brain decides that multiple streams of information are redundant.

In an early review of intersensory bias, Welch and Warren (1980) identified three categories of factors that might influence integration: (i) *The stimulus situation:* the stimulus properties (e.g. size, shape, position, intensity, timing) and other external factors such as the instructions that are manipulated by the experimenter. (ii) The *modality characteristics*: The information in the environment perceived via processing by sensory modalities in a manner that is specific to each modality (accuracy, RT, etc.). (iii) The *observer processes*: historical or experiential factors (knowledge, familiarity) which can affect the observer's assumption of unity and the perceptual outcome. Welch (1999) proposed that non-cognitive factors could be reduced to one, the number of "amodal properties" (such as spatial location, timing, or shape) shared by the two sensory modalities. Moreover, he identified three cognitive factors: (i) the degree to which sensory sources are familiarly related, (ii) the distribution of attention between the two modalities and (iii) the instructional and/or situational modification of the observer's unity assumption. In a recent review of the research on the unity assumption in the context on audio-visual integration, Chen and Spence discussed two additional top-down factors in multisensory perception, i.e. cross-modal correspondence and semantic congruency. Semantic congruency concerns multimodal sensory features referring to the same object or concept (e.g. the image of a dog and a barking sound). Crossmodal correspondence refers to the compatibility between features of unisensory stimuli such as large visual size and high auditory pitch.

While the unity assumption figures prominently in sensory integration research, it is a confusing concept. Welch and Warren (1980) define the unity assumption in this way: "the stronger the observers' assumption that they are in the presence of a single distal object, the greater will be the magnitude of intersensory bias. This assumption is referred to as the *assumption of unity* and its strength is in turn presumed to be a function of the number of physical properties (e.g., shape, size, motion) that are redundantly represented in the stimulus situation, as well as the relative weighting assigned by the observer to these properties" (Welch, 1999, p. 639). This definition suggests that the unity assumption corresponds to an internal state of the observer, which can be influenced by many factors. However, it does not provide a practical way to characterize or assess the unity assumption. Functionally, it is not clear whether the unity assumption is a factor that has an independent effect of its own on sensory integration; or whether it is simply a way of referring to the observer's internal state, which unfortunately cannot be directly observed. A related question is whether the unity assumption must be conscious. Most research has focused on the observable outcomes of sensory integration such as intersensory bias and has remained non-committal about this issue (see Welch & Warren, 1980, p. 662; Chen & Spence, 2017, n. 2; Deroy et al., 2016).

Several attempts have been made to use instructions to manipulate the "unity assumption" independently of sensory inputs (Helbig & Ernst, 2007; Miller, 1972; Misceo, Jackson, & Perdue, 2014; Misceo & Taylor, 2011). In this context, the unity assumption is considered an independent cognitive factor that modulates sensory integration. In this respect, the role of the instructions and task to explain the different results obtained by Squeri et al. (2012) in a curvature discrimination task and by Panday et al. (2013) in a size discrimination task with curved objects should be investigated further using the same stimuli if possible. The effect of instructions in bimanual integration could also be investigated by simply telling the subjects that they are touching the same object or two different ones.

Our results indicate that being able to lift or manipulate an object freely affects bimanual integration. Because free manipulation of an object is such a strong cue that both hands are touching the same object, it is tempting to conclude that free manipulation enhances bimanual integration by strengthening the unity assumption. As noted above, however, it is hard to define precisely what the unity assumption is. An interesting question is whether the effect of this experimental factor is mediated by low-level or high-level processes. At one level, the free and grounded conditions represent different physical constraints among the hands, the object and the environment. The effect of these physical constraints on the sensory and motor signals can be considered non-cognitive factors affecting bimanual integration. Temporal synchrony or spatial congruency are possible examples of this. On the other hand, it is important to mention that the free condition did not provide more information about the *size* of the object with respect to the grounded condition. The main impact is to provide information that the two hands are touching the *same* object, which affects how the available information is processed in the bimanual condition. The determination that the two hands are touching the same object on the basis of the sensory and motor signals must be based on previous experience with manipulating objects and a form of motor cognition.

It should be noted that the physical coupling created by an object held with both hands has important consequences from a motor control point of view. To plan a movement without error and achieve a certain level of dexterity, the brain must coordinate the action of the two hands when they are physically coupled. Interestingly, some studies have shown that a perturbation of one hand can lead to anticipatory adjustments to both hands in bimanual tasks, which suggests that the brain might have internal models for bimanual tasks that integrate this physical coupling (Witney, 2004). An interesting question is whether the internal models that are relevant to bimanual motor tasks are also involved in the processing of sensory information in bimanual perceptual tasks. In other words, in the context of this study, it is possible that bimanual integration when lifting the object could also reflect the bimanual integration happening to control its movement (see more discussion in Appendix A).

The cognitive dimension emerges also when interpreting the results of the box and plier experiments where the observation that we observed bimanual integration with boxes in the grounded condition could be a contextual effect due to our familiarity with manipulating rigid objects like boxes. Previous research has shown that stimulus familiarity has an effect on audio-visual integration (Hein et al., 2007; Walker, Bruce, & O'Malley, 1995). In haptic recognition tasks (Lacey & Sathian, 2014), it has been proposed that familiar objects are easier to recognize because top-down influences can complement or supplement sensory inputs to infer their shape. In contrast, less familiar objects would have to be explored more extensively to create a global representation of their shape in a bottom-up manner (Lacey & Sathian, 2014). It is possible that the lack of a well-defined high-level representation of the pliers hampered the processing of shape information in the grounded condition and the integration of bimanual information. Additional research is needed to find out whether seeing the box or the mere knowledge that one is lifting a box is sufficient to trigger bimanual integration. Another open question is whether free manipulation is a necessary condition to trigger bimanual integration with less familiar objects like pliers.

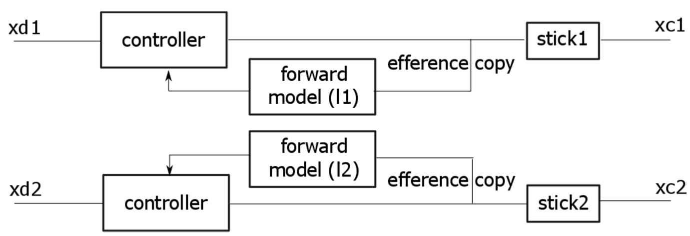
To conclude, bimanual integration is an interesting phenomenon because of the large number of factors that can affect it. None of these factors can single-handedly explain the results of all the previous studies. Like in other sensory integration studies, a mix of structural factors and cognitive factors appear to matter.

Appendix A

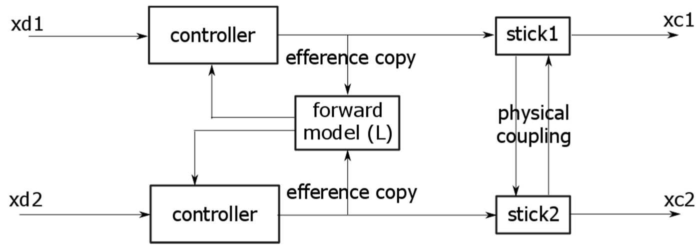
This appendix extends the discussion of the results of the plier experiment in the Study 1. It develops the idea that bimanual integration in perceptual tasks might could be based on and share internal models that are involved in bimanual motor tasks.

When the plier is manipulated in the grounded condition, each hand can control the movement of the two handle independently, without interference from the other hand because the two sticks are not coupled physically. Each hand needs to know only about the properties of the stick that it is controlling. In this condition, there is no reason for the two hands to estimate conjointly the size of the stick. In other words, the parameters of the physical object are likely to be estimated by each hand independently.

The situation is however very different in the free conditions where the two hands interact physically via the pliers and must coordinate their action in order to control the movements of the plier. In this case, it is not optimal to have two independent controllers because independent controllers neglect interaction forces by definitions. For each controller, the action of the other hand is a disturbance. For bimanual action such as moving a tray, it makes sense to assume that control is shared at some level. Accordingly, it also makes sense that the two-hand manipulation contributes to estimating the state and properties of the system, such as the size or weight of the objects.



(a) Grounded condition with constrains on the plier



(b) Free manipulation of the plier

Figure 19. Computational models in human behavior in the plier manipulation.

Figure 19 shows a putative schema that represents the control of the plier in the bimanually grounded (top panel) and free (bottom) conditions. In the top panel, the two hand control the movement of each handle (stick) of the plier independently. A forward model is used by each hand to predict the consequence of the action in a quick feedback loop (see Chapter 1). Each forward model contains a separate estimate of the size of the handle.

In the bottom panel, the two hands share a forward model that predict the state of the plier in the free condition. It is important to note that the physical interaction happens in the free-manipulation control system, which is absent in the grounded condition, might be a key factor that contributes to the integration of the entire system.

Chapter 3: Study two

3.1 Introduction

Reaching movements. As described in more details in Chapter 1, reaching toward a visual target requires transforming the target position into a set of motor commands that moves the hand to the desired position. Early studies have shown that reaching movements can be divided in an initial ballistic phase that reflects the planning of the movement followed by corrective movements that use visual feedback to adjust the final position of the hand (Keele, 1968; Woodworth, 1899). Target position is initially represented in a retino-topic frame of reference and is successively transformed to an hand-centered or body-centered representation (Atkeson, 1989; Andersen & Snyder, 1993; Henriques, Medendorp, Khan, & Crawford, 2002). Interestingly, planar reaching movements tend to have straight trajectory and bell-shaped velocity profile, which requires that shoulder and elbow joints follow a non-linear coordination pattern (Morasso, 1981).

Besides information about the target position, planning a reaching movement also requires information about the body such as the structure of the arm, the length and masses of its segments. Current accounts of these processes give a central to the so-called internal models, which include information about the body and the environment and that are necessary to transform the target position into a set of appropriate motor commands (inverse models) and to predict the consequences of the action (forward models) (Gribble et al., 1998; Kawato, 1999; Shadmehr & Krakauer, 2008; Wolpert, 1997).

A classic approach to understand sensorimotor processes and underlying representations involved in reaching and pointing movements is to study the errors that occur when the natural mapping between sensory signals and motor commands is artificially transformed by wearing prisms or using a tool for example (Cunningham, 1989). Numerous studies have confirmed that this system is flexible and can adapt to changes in the conditions in which the movements are executed. For example, visuo-motor rotations, where an angle is introduced between the direction of the movement of the hand and the direction of the movement of the cursor, have provided a rich experimental ground (Abeele & Bock, 2001).

Tool Use. Using a tool introduces a discrepancy between the tool and the hand positions, which requires adapting the motor commands to bring the tool on the target position. Besides having an impact at the kinematic level, physical tools have also masses and inertial properties that can have a detrimental impact on the trajectory if they are neglected. Tool-use requires therefore not only to learn a new kinematic transformation but also a new dynamic transformation (Krakauer, Ghilardi, & Ghez, 1999).

Even though using manual tools requires in general some learning, the apparent facility with which adults can use different tools is a testimony of the flexibility, adaptability and capacity of the motor system. There is a debate on whether tool-use involves a transformation of the internal model(s) representing the body or the addition of a new model representing the tool (Massen, 2013). On the one hand, neuroscientist and neuropsychologists have suggested that tools are incorporated into the body schema (Cardinali et al., 2009; Maravita & Iriki, 2004; Martel et al., 2016). For example, it has been suggested that using tools (e.g. mechanical grabber) that physically extends the arm length can modify the somatosensory representation of body morphology, leading to an elongation of the corresponding part in the body schema with the results of extending the perceived size of the reaching space (Cardinali et al., 2009). On the other hand, tool-use might also involve distinct action schemata or internal models representing the transformation between hand and tool tip (Norman and Shallice, 1986; Baber 2006).

Articulated objects. The focus of this thesis is on articulated objects or, more precisely, linkages. As noted in Chapter I, a ***linkage*** is an assembly of links and joints that provide a desired output motion in response to a specified input motion (Slocum, 2008). A *joint* is a connection between two or more links at their node, which allows motion to occur between the links. The number of degree-of-freedom is equal to the number of input motions needed to define the linkage motion. In this study, we consider only two-degrees-of-freedom planar linkages with revolute and prismatic joints. Both joints allow only a single degree-of-freedom movement.

Articulated objects have kinematic and dynamic properties that distinguish them from rigid bodies, which raise new issues both on the perception and control sides. Unlike rigid bodies, articulated objects do not have a fixed shape since they are made of parts that can move one relative to another. However, these movements are not completely free because the linkage structure constrains the movement the links along some direction. In all mechanisms considered in this study, all links move together in the sense that the position of one link determines the position of all the other links. In other words, the movement of the whole mechanism might be determined by the movement of one of its part. In fact, mechanisms are often used to transform movements of one kind into movements of another kind. For example, the crank-slider transforms a rotational movement into a linear movement (see Figure 11). Another example is the pantograph which transforms the scale of a movement (see Figure 11). When using articulated objects, the user can control the action of the mechanism by moving one of its link and to obtain a different movement with another part of the mechanisms. One question at the center of this study is whether people have mechanical knowledge that they can use to control the movement of relatively simple mechanisms.

Sülzenbrück and Heuer studies. Our ability to use linkages has been little studied. One notable exception is a series of studies by Sülzenbrück, Heuer and collaborators who have investigated in depth the use of a tool, the sliding-level, composed by a lever that could slide and rotate through a fixed joint called fulcrum (see Figure 11). The most crucial features of the kinematic transformation of this mechanisms are the *fulcrum effect* (Gallagher, McClure, McGuigan, Ritchie, & Sheehy, 1998) and the gain (Sülzenbrück & Heuer, 2010). The fulcrum effect refers to the reversed direction of movement, the direction of the end-position of the lever is inverted corresponding to the movement direction of the hand. The gain is the ratio on amplitudes of movement between the tip of the lever and the hand. The gain value is not constant but depends on the direction and position of the fulcrum on the sliding-lever. It results that straight hand movements produced curved trajectories of the tip of the sliding-lever and vice-versa. The sliding-lever mechanism is representative of the mechanism presented in some minimally invasive instruments such as the endoscope (Sülzenbrück & Heuer, 2011).

In one of their early study with this mechanism, Heuer and Sülzenbrück (2009) found that the trajectory of the tool tip became straighter after a familiarization phase. This observation is in agreement with the idea that the people try to produce straight trajectory when performing point-to-point on a plane (Morasso, 1981). In this context, producing a straight trajectorya required that the hand trajectory becomes more curved which suggests that tool tip (or the cursor representing it) is the primary controlled variable. They suggested that the remaining deviations from straightness in absence of visual feedback could be in part explained by the inertial anisotropy of the tool. A similar explanation has been advancedadvanced to explain patients with proprioceptive loss might be less able to take compensation for interaction torques that arise when moving the arm (Sainburg, Poizner, & Ghez, 1993).

Real versus virtual tool. (Sülzenbrück & Heuer, 2010) investigated whether using real tool was easier or more difficult than a virtual tool. They hypothesized that learning could be simplified by omitting the dynamic transformation and thus that the task might be easier with the virtual tool. However, they found little difference in terms of final accuracy or learning rate between the physical and virtual tool in open-loop tests (Sülzenbrück & Heuer, 2010). One possible explanation for the lack of effect of interaction force is that attention might be focused on the visual input, i.e. the cursor representing the tool tip, rather than proprioceptive input, i.e. the hand position, since the cursor position is the variable that needs to be controlled (Heuer & Rapp, 2012).

Visual feedback is crucial to correct errors when exposed to new visuo-motor transformations and has a dual function: it can be used during the movement to correct errors in closed-loop control and to acquire an internal model of the visuo-motor transformation. Interestingly, there is evidence that visual feedback provided only after the end of the movement (i.e., knowledge of results) might be more effective than continuous feedback with regard to the acquisition of an internal process (e.g. Cohen, 1967; Heuer & Hegele, 2008). Indeed, Sülzenbrück and Heueer (2011) found that movements were more accurate and faster in open-loop tests after practice with terminal feedback. However, the tool trajectory trajectories were more curved with terminal than continuous feedback. They concluded that, in the open loop condition, participants acquired an internal model of the direction and amplitude of the movement needed to bring the cursor to the target position but not the appropriate curvature to produce straight paths (Sülzenbrück & Heuer, 2011).

An interesting pattern that emerges from their studies is the interaction between the type of lever and the type of visual feedback with respect to the curvature of the trajectories. While the movement of the cursor are approximatively straight with continuous feedback, they found that cursor movement are more curved and hand movements tend to be straight with terminal feedback when using a virtual tool (Sülzenbrück & Heuer, 2011). However, using a physical tool makes cursor movements straighter and hand movements more curved even with terminal feedback (Heuer & Sülzenbrück, 2009; Sülzenbrück & Heuer, 2010). To explain this observation, they proposed that interaction force might redistribute attention to proprioceptive (Sülzenbrück & Heuer, 2011).

It should be noted in all Sülzenbrück & Heuer studies, the participants were not shown the physical tool, which was hidden by an opaque screen, perhaps because they were primarily interested in understanding how participants learn to master the complex visuo-motor transformations induced by the tool in a context - micro-surgery - where the tool mechanics is hidden. The movement of the tool tip were represented by a cursor displayed on vertical screen in front of the tool. The virtual tool was also represented only by the cursor movement on the screen. A question that remains therefore unaddressed is whether seeing the tool could help participants in forming a mental model of the visuo-motor transformation, which might have helped them to control the movements of the cursor.

Objectives. The main objective of this study was therefore to find out whether seeing the mechanism provided useful and actable information to the subject *in addition* of the information provided by visual feedback on the position of the *tool tip, which remained always visible*. The central hypothesis is that the participant might have some mechanical knowledges of linkages, which could be used to predict the motion of the whole mechanisms when moving one of its parts and facilitate the use of the tool. In other words, the idea is that it might be easier to reach the target if one sees the mechanisms in addition of the movement of the end-effector. To that end we studied the performance of participants in conditions the tool was visible and not visible. All the tools considered in this study were planar linkages with two degree-of-freedom, which differed in the number of links and the type of joints (revolute or prismatic).

A second objective was to find out whether seeing the mechanism might help already in the planning phase, or if it is more useful during the execution of the movement. To that end, we included three different visual feedback conditions: a condition vision of the mechanism as baseline; a condition where the mechanisms was shown for a brief time interval before the beginning of the task; and a condition where the mechanism remained visible during the task. Note that the position of the end effector was always visible in all conditions.

Therefore we propose two hypothesis. The first hypothesis is that vision of the time-varying mechanism configuration improves the visuo-motor control performance in the reaching task. Thus, a performance improvement when seeing the mechanical linkages would demonstrate an ability to use this information to control the movement of the cursor by anticipating the necessary trajectory changes at the level of the hand. A second hypothesis is that visual information of the mechanism helps in the planning phase of control movement. Ideally, if the subject were able to use the visual information about the linkage to predict the trajectory of the cursor, they should be able to perform as well as in absence of any transformation.

This study intentionally was designed to limit learning and/or transfer opportunities. First, the participants had a limited exposure to each mechanism and target positions were randomly generated and thus involved different movement directions and/or workspace regions. Moreover, the tool changed randomly between each block and were separated by a block of visuo-motor rotations, which might contribute to wash out memories the previous.

In the following, we report the result of three experiments. In the first experiment, we compared the effect of the three types of feedback on the control of six different linkages. This experiment is followed by two control experiments that aim at clarifying some issues raised in the main experiment. The experiments were conducted during a secondment in Prof. Brenner's laboratory at the University of Amsterdam that was part of the PACE International Training Network program. The main finding is that seeing the mechanism improves the performance as long as the mechanisms is visually simple.

3.3 Experiment one

3.3.1 Method

Participants

Eighteen participants (eight males and ten females) took part to this experiment. All participants were naïve to the goal and content of the tasks. Among the 18 subjects, three were left-handed (for writing and drawing according to Edingburgh handedness test questions). No participants reported a hand deficit. The experiment was complied with ethic principles, all participants signed an informed consent approved by the local ethical committee before the start of the experiment.

Experimental setup

The experimental setup consisted in a large trackpad with a resolution of 1920 x 1080 pixel (1.1 x 0.7m in physical dimensions) and refresh rate at 60 Hz. The motion of the hand-held stylus on the track pad was recorded at 60 Hz during the experiment to display the proper visual feedback on-line and for off-line analysis.

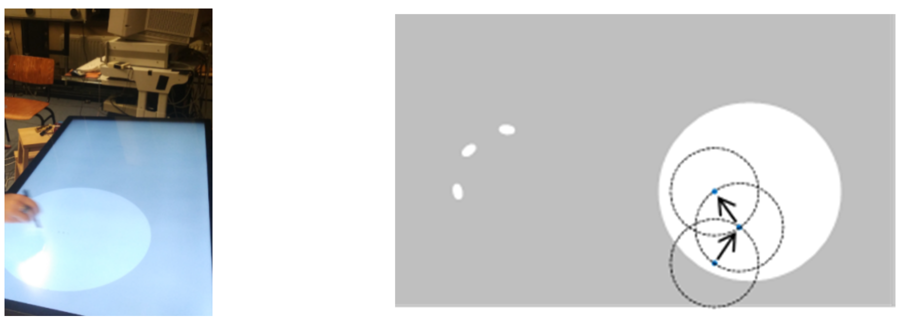


Figure 20. Visuo-motor reaching experimental setup. (a) Trackpad used during the experiment. (b) Illustration of corresponding target positions in the hand space.

Task and experimental procedure

The experiment consisted in a series of reaching movements, grouped in blocks of 30 seconds. The task was to reach as many targets as possible during each block.

The hand movement was restricted to the hand space, a large circular area shown in white color on the right side of the trackpad (see Figure 20). The radius of the hand space was 384 pixel centred at (1440, 432). The sequence of target positions was computed by randomly selecting a point at a distance of 300 pixels from the previous target in the hand space. Then, this position was transformed in the cursor space (the grey area outside the hand space) and displayed as small white oval or circular disks, which corresponded to a small circular disk in the hand space. This procedure insures that the task difficulty (movement amplitude and precision requirement) in the hand space remained constant in all conditions.

The experiment started with a familiarization section of three standard blocks where the visuo-motor transformation was a simple translation that shifted the cursor position outside the hand space without other transformation. At the beginning of each block, the participant could explore the new visuo-motor transformation for 5 seconds. Then, a short alarm beep indicated the apparition of the first target. As soon as a target was reached, it disappeared and a new target appeared up. Reaching a target required to stay over the target area with a velocity smaller than a pre-set threshold.

Participants were asked to keep the stylus in contact with the screen during the entire experiment. The cursor and hand positions were always shown as two small blue dots unless the stylus existed from the hand space in which case the hand cursor along with the configuration of the mechanism(if applicable) disappeared until entering the hand space anew.

Visual feedback

The experiment included two types of blocks: blocks that corresponded to one of the mechanisms and blocks that corresponded to a visuo-motor rotation. For blocks that corresponded to a mechanism, there were three visual feedback conditions:

- a 'Visible' condition where the configuration of the articulated mechanism was visible on the screen during the entire block;
- A 'Pre-visible' condition where the mechanism was visible only during the first five seconds set for free exploration and then disappeared when the first target appeared;
- An 'Invisible' condition where the mechanism was not shown.

In all three conditions, the hand and cursor positions were marked by blue dots that remained visible throughout the experiment.

Mechanisms

Blocks with a visuo-motor rotation alternated with blocks with a mechanism. Each mechanism was presented only once in each visual condition. While rotation blocks alternated with mechanism blocks, the order of presentation of the mechanisms and rotation angles was selected randomly within the constraints that each visuo-motor transformation be presented only once.

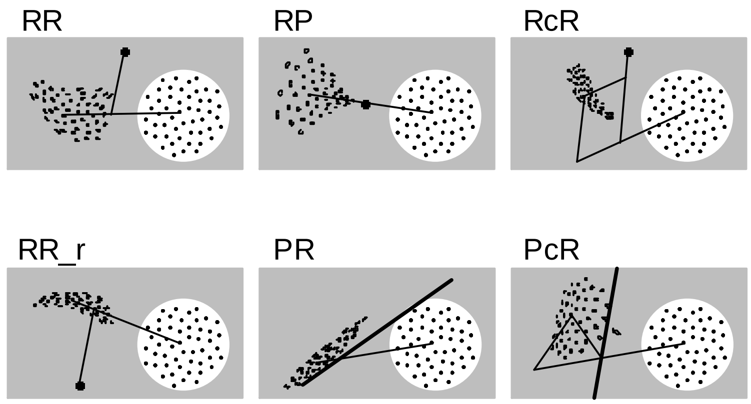


Figure 21. Mechanisms presented in the first experiment. The revolute joint or link fixed to the ground is represented by a back dot or a thick line.

All mechanisms corresponded to planar linkages with two degrees of freedom were controlled by moving the extremity of the link inside the hand area while the end-effector (aka, the cursor) corresponded to the extremity of a link or a joint position (see Figure 21). The hand and cursor position were marked by a blue dot on the screen, which remained visible in all visual feedback conditions.

RR and **RR$_r$**: The simplest mechanism was composed of two articulated rods and two revolute joints (RR). One extremity of the first link is anchored to the ground via a revolute joint while the other extremity connects to the middle of the second link. The extremities of the second link corresponds to the hand and cursor position respectively.

RRcRR: This mechanism included four revolute joints and a closed-loop chain (RR constrained by RR, abbreviated as **RcR** in the figure). It is based on the RR mechanism with the important difference that the cursor corresponded to the revolute joint in the middle of the RR closed loop chain.

RP: The RP mechanism has one link and two joints. Starting from the ground, the RP mechanism has revolute joint that allows the rotation of a prismatic joint. The prismatic joint allows a sliding movement of the link. This mechanism is has the same structure as the ‘sliding-lever’ used in Sülzenbrück & Heuer studies. The two extremities of the sliding link correspond to the hand and cursor position respectively.

PR: The PR mechanism has two links and two joints. The prismatic joint is mounted on a link fixed to the ground followed by a revolute joint that allows the rotation of the second link. The two extremities of the second link correspond to the hand and cursor position respectively.

PRcRP: This mechanism has two prismatic and two revolute joints forming a closed-loop (PP constrained by RR). The first link is fixed on the ground and the second link fixed to the first link via two non-orthogonal prismatic joints. The two remaining links and revolute joints form a closed-loop chain that play no role with respect to the movement of the second link. The hand position correspond to an extremity of the second link correspond while cursor correspond to the revolute joint position in the middle of the closed loop chain.

Visuo-motor rotations

As noted above, the 18 blocks with mechanisms (six mechanisms by three visual feedback conditions) alternated blocks with visuo-motor rotations. The rotation angle for each block ranged from -120 to 120 degree in steps of 15 degrees. A different rotation was used for each visuo-motor rotation block in a random order.

Data Analysis

We recorded the position of the hand cursor and the corresponding controlled cursor position. For each movement, we determined the movement time and trajectory length. The total number of targets achieved in each block was calculated and used as performance index in the analyses.

A technical problem related to the labelling of the mechanisms in the program led some participants to perform twice RR (7 participants) or RR_r (4 participants) instead of once each. For this reason, we used a linear mixed-effect model (LMM) to analyse these data with mechanism (6 levels) and visual feedback (3 levels) as categorical predictors. In this analysis we eliminated the second performance of the participants who were erroneously exposed twice the same mechanism, which yielded a data set with 11 subjects who had missing data for either the RR or RR_r mechanism. It was not possible to fit the full variance-covariance matrix for the random effects. Likelihood ratio tests, Akaike information criterion (AIC) and Bayesian information criterion (BIC) revealed that a slightly simplified variance-covariance allowing correlations only within the levels of the two predictors did not fit better the data than a covariance matrix for a simple random intercept model. Tests of significance of the fixed-effects were very similar for the two models. The p values for fixed effects were computed with Kenward-Roger approximation for degrees-of-freedom. We also performed a two-way repeated-measure ANOVA on the seven subjects who had been exposed to all mechanisms with p values adjusted for the sphericity condition with Greenhouse and Geisser (ges) epsilon. The results of both analyses are reported in the Results.

Finally, we performed one-way RM ANOVA to statistically test the effect of rotation.

3.3.2 Results and Discussion

This section focuses on the performance obtained with the mechanisms. All the visuo-motor rotation conditions are analysed together with the results of the other two experiments later.

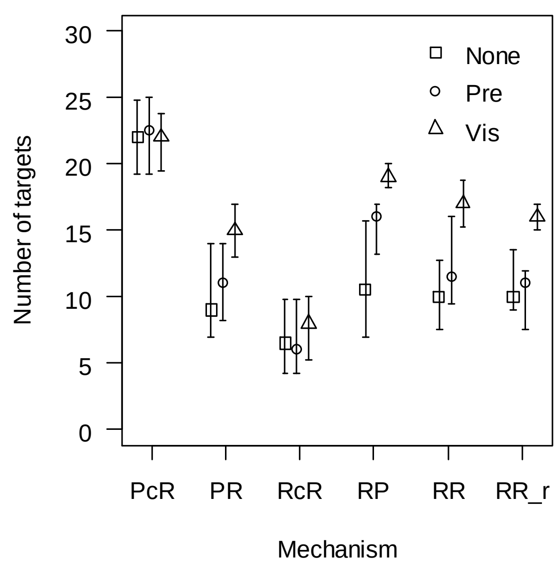


Figure 22. shows number of targeted reached across tools and visual conditions. Vertical bars represent the standard error.

The performance ranged from only 7 to almost 22 targets reached within 30 seconds depends on the mechanism (see Figure 22). This large range shows considerable variations in the difficulty of the visuomotor transformation associated with these tools.

Figure 22 shows that the performance measured in terms of the number of targets differed considerably across mechanisms, ranging from 7 for RcR to more than 22 for PcP. The performance improved when visual feedback was given for most mechanisms, with the exception of the RcR and PcP mechanisms. The LMM analysis with all subjects show a strong effect of mechanism ($F(5, 258) = 103.57$, $p<0.001$), visual feedback ($F(2,256)=33.47$, $p<0.001$) and interaction ($F(10,256)=5.03$, $p<0.001$). Similar results are obtained when performing a two-way repeated measure ANOVA on the subset of participants who were exposed to all mechanisms (N=7), which shows that the effect of mechanism configuration ($F(5,30)=40.33$, ges=0.63, $p<0.01$) and visual presentation ($F(2,12)=22.33$, ges=0.13, $p<0.001$) on the reaching performance are significant. A significant interaction effect is also found between mechanism configuration and visual presentation ($F(10,60) = 3.06$, ges=0.20, $p=0.003$).

A particularly intriguing finding is that the effect of visual feedback does not seem to be related to the performance or, in other words, to the complexity of the visuo-motor transformation. As a matter of facts, vision of the mechanisms failed to bring an improvement for the easiest (PRcPR) and the most difficult (RRcRR) linkages. Interestingly, these two mechanisms share a couple of features. First, they are the only mechanisms with four links. Second, they are the only mechanisms where the cursor is not fixed on the same link as the hand position. As a result, these mechanisms are also the only mechanisms where the distance between the hand and the cursor varies.

3.4 Experiment two and three

The results of the first experiment indicate that seeing the mechanism, even briefly, can improve the performance with respect to a condition where only the position of the end effector is visible. However, such an improvement was not observed for all mechanisms.

The first objective of the second and third experiments is to better understand what distinguishes these two mechanisms from the other ones. In light of their characteristics, we formulated two hypotheses:

1. **The number of link hypothesis.** One possibility is that this effect is related to the difficulty of processing the visual representation of the mechanism and, thus, to the visual complexity. As a matter of facts, the two mechanisms where visual feedback failed to improve performance, PPcRR and RRcRR, are the only mechanisms with four links.
2. **The rigidity hypothesis.** Another possibility is the this effect is present only when the distance between the hand and the cursor is fixed as if they both belonged to the same link.

In order to distinguish between these two hypotheses, we included a new linkage also composed of four links where the distance between the hand and the cursor was fixed (RcRt1). According to the “number-of-link” hypothesis, there should not be a visual effect for this type of mechanisms. In contrasts, the “rigidity” hypothesis predicts that there should be a visual effect.

A second objective was to examine whether there is a categorical distinction between linkages where vision of the mechanism is helpful and mechanisms where it is not. To that end, we introduced two series of linkages:

1. **"P" linkages:** The first series of linkages formed a continuum between a two-link linkage (RR) the manipulation of which was helped by its vision and the four-link linkage (RRcRR) the manipulation of which was not help by its vision. The series was obtained by varying the distance between the two “horizontal” links of the "parallelogram" in the RRcRR linkage. If the number of links was the only aspect that mattered, the prediction is that the benefit of seeing the mechanism should

suddenly disappear when using any of these linkages. Alternatively, there might be a progressive increase of the beneficial effect of seeing the linkage.

2. **"T" linkages:** The second series of linkages formed a continuum between the four-link mechanism RRcRR and the new linkage introduced in this experiment. These linkages might be useful to examine whether there is a sudden or gradual variation of the strength of the visual effect in the case where the rigidity hypothesis would be confirmed.

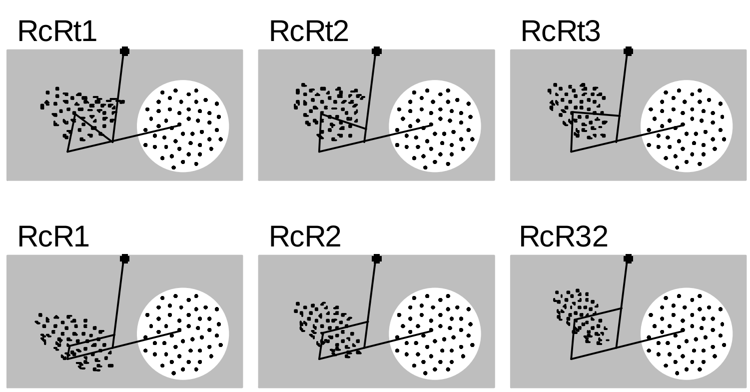
Note that Experiment 3 extends this series of linkage by considering linkages with a parallelogram size more similar in size with the original linkage RRcRR of Experiment 1. The results of the two experiments are reported together.

3.4.1 Methods

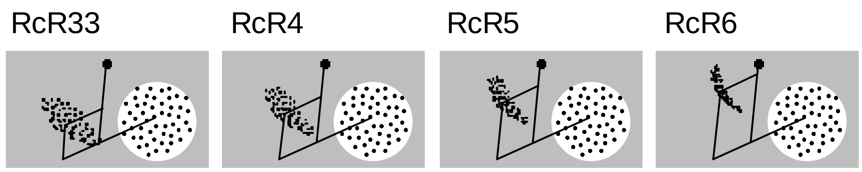
Participants

The study included two experiments. Eighteen (18) participants took part to the second experiment, and 19 to the third experiment. All participants were naïve to the goal and content of the tasks. Among the 37 subjects in total, five were left-handed (for writing and drawing according to Edingburgh handedness test questions). No participants reported a hand deficit. The experiment was complied with ethic principles, all participants signed an informed consent approved by the local ethical committee before the start of the experiment.

Mechanisms



(a) ‘T’ and ‘P’ mechanisms in the second experiment



(b) 'P' Mechanisms in the third experiment

Figure 23. Mechanisms presented in the second and third experiments.

All the mechanisms included in the second and third experiments are derived from the ‘RRcRR’ mechanism in the first experiment.

In the second experiment, the P series included the (‘RcR1’, ‘RcR2’ and ‘RcR32’) in addition of the two-link RR mechanisms already present in the first experiment. The distance between the two "horizontal" bar corresponded to 20% (RcR1), 40% (RcR2) and 60% (RcR32) of the distance of the original parallelogram RRcRR in experiment 1.

In the third experiment, we extended the series by including linkages with a distance between the two horizontal bar corresponding to 60% (RcR33), which had the same size as the largest rectangular mechanisms in Experiment 2, 80% (RcR4), 100% (RcR5), which has the same size as the original RRcRR mechanism in Experiment 1, and 120% (RcR6). Note that there were small variations in the position of the fixed point across experiments to insure that all positions in the hand space could be reached.

For the "T" series in the second experiment, the linkages were obtained by displacing the position of the revolute joint link that closed the loop on the first link and progressively transforming the original parallelogram loop in ‘RRcRR’ into a 'triangular' loop (see Figure 23.a). The new positions of the revolute joint on the first link correspond to 40% (RcRt3), 20% (RcRt2) and 0% (RcRt1) of its position in the original parallelogram (RRcRR in Experiment 1).

Visual feedback

The second and third experiments involved the ‘Visible’ and ‘Invisible’ visual feedback conditions only. The two visual feedback conditions were the same as in the first experiment. In the ‘Visible’ condition, the configuration of the articulated mechanisms was presented on the screen during the entire block whereas, in the ‘Invisible’ condition, only the hand and cursor positions were visible.

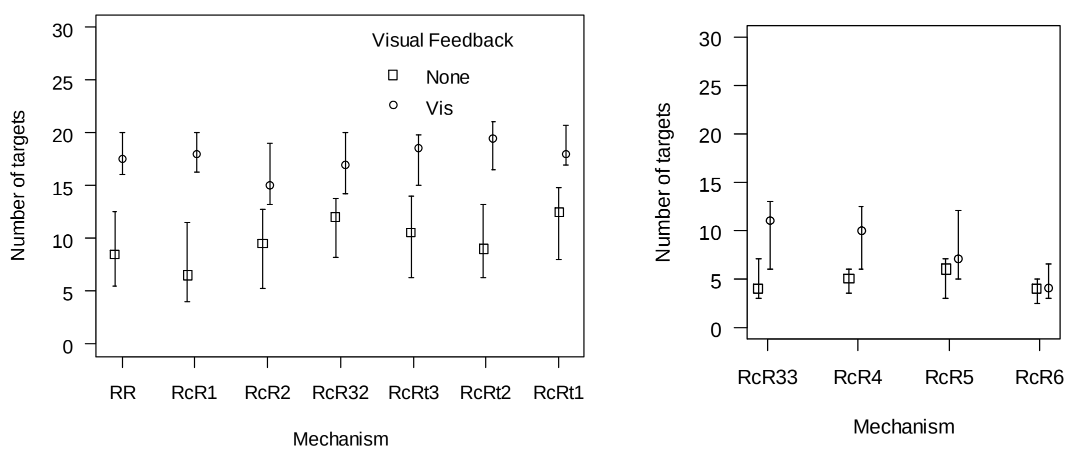
Visuo-motor rotations

In the second experiment, the rotation angle ranged from -90 to 90 at 15-degree steps while the third experiment included 7 rotations from -120 to 120 degrees (±120, ±75, ±30 and 0 deg). In the rotation blocks, only the cursor and hand positions were visible.

Data analysis

As in the first experiment, the number of targets reached in 30 seconds corresponds to the main index of performance. We performed repeated-measures ANOVAs to analyze the effect of mechanisms and visual feedback separately for each experiment. The p values were adjusted for the sphericity condition with the Greenhouse-Geisser (ges) epsilon.

3.4.2 Results



(a) Number of targets across mechanisms and visual conditions in experiment 2

(b) Number of targets across mechanisms and visual conditions in experiment 3

Figure 24. Effect of mechanism configuration and visual representation on the performance.

We first analysed the results of experiments 2 and 3 separately. For experiment 2, Figure 24 (a) shows that vision of the mechanisms improved the performance with all mechanisms of Experiment 2. This observation is confirmed by a two-way repeated measure ANOVA with the mechanism and visual feedback as within-subject factors that shows that only the main effect of visual feedback is statistically significant (F(1,17) =

242.5, $p<0.001$). The mechanism ($F(4.5,76.7) = 2.30$, ges=0.036, $p=0.06$) and, in particular, the interaction ($F(4.5,76.0)=1.262$, $p=0.29$) were not statistically significant.

Number-of-link hypothesis . As in the first experiment, vision of the mechanism improved the performance for the two-link mechanism RR in experiment 2 (paired t test: $t(17)=6.57$, $p<0.001$). However unlike the four-link mechanims in Experiment 1 (i.e., RRcRR or PRcRP), this was also the case for all four-link mechanism of Experiment 2. In fact, paired t tests conform a statistically significant effect of seeing the mechanism for all mechanisms in experiment 2 (results not reported). These observations disprove that the number of links is critical factor to be able to use the information provided by seeing the mechanism.

Rigidity hypothesis The beneficial effect of seeing the mechanism was also present for RRct1 (paired t test: $t(17)=5.41$, $p<0.001$), where the distance between the hand and cursor position is fixed. This observation indicates that seeing the mechanism can improve performance whether the relative positions of the hand and cursor are fixed (RRct1) or not (all other mechanisms) and disproves the rigidity hypothesis.

In summary, the results of the second experiment disprove the two hypotheses set forward initially on the basis of the distinctions that were present between mechanisms that benefitted from being able to see them and not in Experiment 1. To explain the discrepancy between the results of Experiment 1 and 2 with four-link mechanism, it should be noted that none of the mechanisms included in Experiment 2 corresponded to one of the four-link mechanisms of Experiment 1. In particular, the size of the `parallelogram` mechanisms in Experiment 2 were all smaller than the corresponding mechanism in Experiment 1 (RRcRR). Finally, it might be noted that the difference between the conditions with and without vision of the mechanism appears to decrease as the size of the parallelogram increases in Experiment 2.

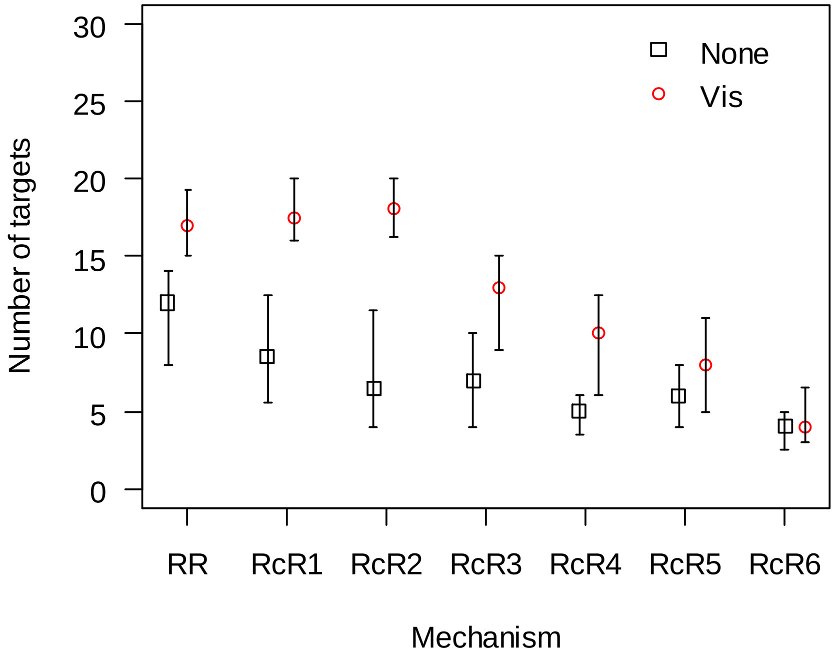


Figure 25. Results for the parallelogram linkages in the three experiments. Vertical bars corresponds to SE. RcR5 corresponds to RcR in Experiment 1. The horizontal axis correspond to the length of the link between the other extremity of the hand-held link and the cursor position (ld).

The results for the four-bar rectangular linkages of all three experiments are summarized in Figure 25. There was a clear influence on the visual effect as the distance between the two parallel bars increased ($F(1,8)=24.52$, $P<0.001$). The size of the effect for the RR and RRcRR linkages is consistent across experiments.

Clearly, we did not find sudden transition of the strength of the visual effect between the two-link (RR) linkage and the other 4-link linkage. These results with parallelograms suggest that the visual effect is most helpful when the mechanical linkage is easy to interpret visually. This is the case when the linkage has only two links or, for parallelograms, the two horizontal and parallel links are close. As the distance between these two links increase, it becomes more difficult to interpret visually.

3.5 Visuo-motor rotation

In this section we present the results of the visuo-motor rotation condition across the three experiments.

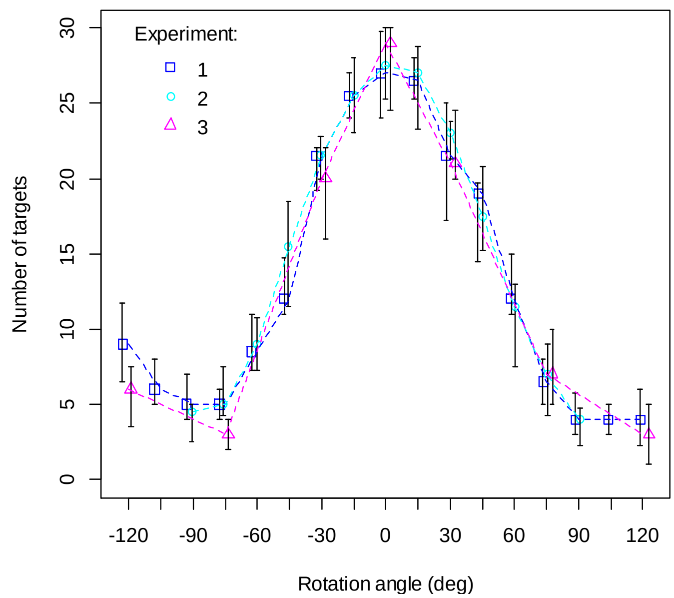


Figure 26. Effect of Rotational angles on the performance (vertical bars corresponds to SD).

Figure 26 presents the performance in rotational transformation conditions as a function of the rotation angle. The performance ranged approximately from only 3 to almost 30 targets reached within 30 seconds. This figure shows clearly an effect of the rotation on the performance (separate one-way RM ANOVA for each experiment confirmed the rotation effect: $F(16,272)=155.8$, $ges=0.85$, $p < 0.001$, for Exp. 1; and $F(12,300)=247.8$, $ges=0.87$, $p < 0.001$, for Exp. 2; and $F(6,150)=289$, $ges=0.87$, $p < 0.001$, for Exp. 3). Interestingly, the performance was worst at 90 degree and tended to improve for larger rotation angles.

3.6 General Discussion

The first objective of this study was to find out whether seeing the mechanism in addition of the position of the cursor provided improved the performance in reaching movements. We found that seeing the mechanisms, even briefly, improved the performance for most mechanisms. This observation indicates that the participant are able to interpret the visual information in a way that is immediately useful. At the same time, we also found out that seeing the mechanism did not always helped. Interestingly, the benefit brought by seeing the mechanism appeared to be unrelated to the complexity of the visuo-motor transformation since we did not observe any benefit for the easiest (PPcRR) and most difficult (RRcRR) linkages in the first experiment.

In second and third experiments, we tested the hypothesis that the benefit of seeing the mechanism might be related to the number of links since the two mechanisms that did not show this effect had four links in the first experiment. The idea was that four-link mechanisms might be mechanically too complex to analyse (perceptively or internally). We also tested the hypothesis that a fixed relationship between the hand and cursor position, as if they were fixed on the same link, could determine the usefulness of seeing the mechanism. The result of these two experiments did not show any abrupt disappearance of this effect with four-link mechanisms or with the appearance of relative motion between the hand and cursor. However, they revealed that the benefit of seeing the mechanisms progressively decreased with the size of the parallelogram and, thus, the distance between the hand and the cursor.

Altogether, we would like to propose the following interpretation of the results of this study. All the mechanisms in the first experiment where vision helped (i.e., RR, RR_r, PR and RP) shared the characteristics that the hand and cursor were on the two extremities of a link that can pivot on a revolute joint in the middle, like a lever. We hypothesize that this configuration might be (i) easy to pick up visually and (ii) useful to control the mechanism. We propose that the decrease of the utility of seeing the mechanism when the size of the parallelogram increases in Experiments 2 and 3 reflects a decrease of the utility of this simplified model of the mechanism that the subject holds. If, as we proposed above, this internal model is essentially the model of "lever" with a controlled position that corresponds to the distal extremity of the lever, then one would expect this model is most useful when the cursor coincides with the controlled position. The benefit of seeing the mechanism would also decrease as the distance between controlled position and the cursor increases.

A special mention must be made for the mechanism PPcRR in the first experiment because it is kinematically very different from the other mechanisms. This mechanism is the only mechanisms where the two degrees-of-freedom correspond to two (non-orthogonal) prismatic joints. It is the only mechanism that does not invert the cursor movement direction with respect to the hand movement direction. As a result, the kinematic transformation is simpler. In fact, the performance with this mechanisms is very similar to the performance observe in absence of any transformation (e.g. rotation angle 0). In contrast, all other mechanisms have a revolute joint in the middle of the hand-held link. As a result, the direction of the movement of the hand and the direction of movement of the cursor are inverted (i.e. a fulcrum effect). For this mechanism with a simple transformation, the results suggest that a model is hardly needed because the performance is already very good when only the cursor position is displayed (the difference between the rotation with 0 degree angle and the value obtained here is 4.83±3.59). For such a transformation, there is limited room for improvement by showing the mechanism (ceiling effect).

When is the model used? A second objective was to find whether the benefit of seeing the mechanism would also occur if the mechanism was shown only at the beginning of the trial. We found that it was also the case, but to a more limited extent. This latter result suggests that having seen the mechanism might help in the planning (and/or control) of the successive movements. The observation that there is additional benefit in seeing the mechanism during the execution of the movement suggests that it also improves the efficiency of the involved in corrective action.

While our results hint at an effect at a planning stage, it is not possible to conclude strongly that the temporary vision of the mechanism at the beginning of the task resulted in an improvement of the planning of the action. To reach such a conclusion, it would have been useful to include open-loop control condition where the cursor position was not visible. It is also possible that an analysis of the initial part of the trajectory would show a difference with respect to the condition where the mechanism was always visible. We are currently completing these analyses.

How exact is the internal model of the mechanism? It is important to note that the improvement brought by the vision of the mechanisms was limited. Ideally, if the participants were able to use the visual information to build a precise model of the linkage, they should be able to perform as well as in absence of any transformation. However, for all linkages where an improvement could be observed, the performance was worse than that could be observed in absence of any visuo-motor transformation (e.g. see 0 degree rotation). These results show that the information gained by seeing the linkage could not fully compensate the changes introduced in the visuo-motor transformation by the mechanism. A possible explanation is that the internal model associated to the vision of the mechanism might be an approximation of the actual linkage transformation.

There is evidence that the acquisition of internal model of a new visuo-motor transformation involves a progression of simplified models, such as the point symmetry or line symmetry approximation. For instance, large visuo-motor rotations are initially approximated by a point-symmetric transformation (Abeele & Bock, 2001; Bock, Abeele, & Eversheim, 2003). Similarly, (Sülzenbrück & Heuer, 2009) found that a line-symmetry approximation predicted well the initial adaptive shifts that they observed with their sliding-lever mechanism, followed by a fine-tuning and a final state that was in between the line-symmetry and the true transformation (see also Sülzenbrück & Heuer, 2010). In our study, it is possible that the vision of the mechanisms might have provided only a simplified model of the kinematic transformation of the mechanism, or that it might have relied on existing knowledge that corresponds to a simple approximation of the mechanism. For example, the line-symmetry approximation model might have been used to model the fulcrum effect in our study (Sülzenbrück & Heuer, 2009).

A limitation of the current study is the absence of an open-loop condition, which might have allowed us to identify the internal representation of the target position in absence of any visual feedback (without the cursor). The analyses of the beginning of the trajectories might provide some hints in this respect but future research should include an open-loop condition to identify more precisely which approximation or simplified model might have been gained from seeing the mechanism.

Cognitive or embodied model? Recent work on learning novel visuo-motor transformation suggest that different process might operate in parallel. In particular it has been suggested that explicit cognitive strategies might be involved at the beginning (Heuer & Hegele, 2015; Taylor & Ivry, 2011). Although implicit models are usually associated with relatively slow learning processes, it is interesting to note that there is evidence that tool use can have an immediate effect, in particular if the tool is a simple stick. For example, Berti and Frassinetti found that using a stick allowed a neglect patient to perform a bisection in the far space without any specific training (Berti & Frassinetti, 2000b).

Similarly, Maravita *et al.* found that using a stick immediately affected the distance at which cross-modal extinction occurred in a patient where extinction was stronger in the near than the far space (Maravita, Spence, Kennett, & Driver, 2002b). Carlson et al. found that the afterimage of hand-held object in the dark fades faster, which replicate a previous finding that the afterimage of the hand that is moved also fades faster (Carlson, Alvarez, Wu, & Verstraten, 2010). The fading is taken as an indication that the object is assimilated into the body schema: it fades during movement because the new object location is in conflict with proprioceptive signals. Because the grasping of the object, the constitution of the afterimage, the beginning of the movement and the ensuing fading happen in a few seconds, the results of this experiment suggest that object might be incorporated into the body scheme very quickly. Ganesh et al. tested whether spatial location were reachable by the hand alone or by a hand-held tool (the tool could either extend or shorten the reach) (Ganesh et al., 2014). Crucially, the tool and no-tool conditions were mixed to avoid adaptation. They found that the use of a tool lead to an immediate shortening of the limb length representations.

In contrast with many studies involving tool use, this study did not focus on learning the new visuo-motor transformation introduced by the mechanisms. It investigated whether seeing the mechanism would lead to an immediate improvement of performance. Although we propose that seeing the mechanism might have elicited a simplified model of the mechanism, it remains to be seen the planning and execution relied on an cognitive/explicit or implicit/embodied model (Pezzulo et al., 2011).

Articulated objects and tool-use. The results of our study suggest that people have some knowledge about the motion of the mechanisms, which they might have gained from seeing and using simple machines such as pliers, transmission gears, pulleys, and/or, more speculatively, from some embodied mechanical knowledge because the human body is itself a collection joint-connected links. One interesting question is where such a knowledge might fit in current accounts of cognitive and brain processes involved in tool-use.

In a recent review of the literature on tool-use, Osiurak et al. made a distinction between the physical level (i.e., what is objectively observable, the potential relationships between the hand, the tool and the object) and the neurocognitive level (i.e. what the user might perceive or know about these relationships) (Osiurak & Badets, 2016). In their taxonomy, these two levels cross another distinction between three systems: motor control, mechanical knowledge and function knowledge associated with the dorso-dorsal, ventro-dorsal and ventral systems respectively. Finally, Osiurak *et al.* made also a distinction between simple and complex tool uses. Tool uses that amplify the movement of the upper limb are considered simple. In contrasts, tools that convert movement of the hands into a qualitatively different mechanical actions (e.g. using a knife to cut or a pencil to write) are complex. Simple tool-use would involve primarily the dorso-dorsal system, which responds to “structural” or “extrinsic” object properties such as their size, shape, position and orientation in space and is specialized in on-line processing. In contrast, complex tool use would also involve the ventro-dorsal system, which would contain “sensory motor” or “mechanical” knowledge (“gesture engram”) about tool manipulation. This knowledge would include information about how to use a knife to cut or a spoon. Mechanical knowledge would be in charge of forming a mental simulation of the tool use action.

This general framework does not provide, however, an obvious place for the use of mechanisms like those considered in this study. On the one hand, the use of a linkage to perform pointing or reaching movements does not change the nature of the hand action. On the other hand, the movement of the cursor is not a simple amplification of the hand movement. All linkages considered in this study involve position-dependent directional and amplitude distortions. The spatial relationship between the hand and cursor movement is more complex than the condition as using a stick or a rake that extends the length of the hand or forearm. In a sense, the use of an articulated tool will clearly recruit the dorso-lateral system to process spatial information and correct for end-point error. At the same time, the performance improvements related to the vision of the linkage suggest that this process can be informed by mechanical knowledge, which might involve the ventro-dorsal system. From a mechanical engineering point of view, extracting useful information about this transformation from the visual representation of the mechanism requires an understanding of the relative motion of the links and the nature of the joints, i.e. some forms of mechanical knowledge. At the same time, it should be noted that this type of mechanical knowledge is different from the one envisioned by Osiurak *et al.* (2016) which is more related to the function of the tool (e.g. how to use a knife to cut). In the future, it would be interesting to study with brain imaging techniques whether vision of linkages recruit the ventro-dosal system.

Chapter 4

Study three

4.1 Background

Physical objects have ***dynamic properties*** in addition of their geometric or spatial properties. In this context, dynamic properties refer to the object properties that characterize the force arising when manipulating the object.

Dynamic properties include the object's mass and inertia for example. Most studies on the perception of dynamic properties have focused on simple object properties such as their mass or compliance. However, the dynamic properties of rigid bodies and articulated objects are more complex. One question of interest is the extent to which the perceptual system can make sense of the interaction force arising during their manipulation to gain information about the objects. This section starts with a briefly review of the dynamic properties of different classes of objects and previous studies of force perception.

4.1.1 Point mass

From a dynamic point of view, the simplest object is the point mass object where all the mass is concentrated at a single point. In principle, two different cues can be used to ***estimate the mass*** of an object on Earth: the objects' ***weight and its inertia***. The object's weight corresponds to the gravitational force $F_G = g \cdot m$, and is proportional to the mass. The object's weight can be perceived without moving the objects and has been often used to investigate force perception.

In fact, it is known since the 19th century that the discrimination of weight was observed and confirmed to be precise with touch alone (Ferrier, 1886). Successive studies have shown that the manner of obtaining the stimuli has a strong effect on human ability to weight discrimination. For example, studies on weight perception showed that discrimination thresholds decreased when moving the object (Brodie & Ross, 1985). A possible explanation is that subject perceived inertial force when *actively* manipulating the object in addition of its weight, as a result the discrimination capacity improved (Brodie & Ross, 1985; Jones, 1986).

Baud-Bovy and Scocchia (2009) measured the effect of moving an virtual object on the perception of the mass, using an admittance-controlled haptic device (Haptic

Master, Moog FCS robotics), which displayed the inertia masses in a zero-gravity virtual environment as if sliding on a frictionless table. The results showed that movement amplitude and pace influenced the perception of the mass of the manipulated object. In particular, participants perceived *a lighter mass that was moved faster or over a longer distance* as equally heavy *as a heavier mass that was moved more slowly or over a shorter distance*. The authors hypothesised that participants might use maximum force $\mathrm{F_{max}} = \mathrm{M} \cdot \mathrm{a_{max}}$, as a cue for mass. However, the changes in perceived masses corresponded only to about 30% of the change in peak forces, which suggests that mass perception is partially invariant (Baud-Bovy & Scocchia, 2009).

Bergmann Tiest and colleagues (2010) investigated this topic again more recently in order to fully understand the relationship between various modes of mass perception, in particular the difference between static perception through gravitational cues, and dynamical perception through inertia cues. They hypothesised that active touch suppressed force perception, and tested mass perception when holding the mass statically, or while being accelerated or decelerated by hand. The accelerated mass was perceived as much larger than that in the static condition, resulting from the weight (Bergmann Tiest & Kappers, 2010).

4.1.2 Rigid bodies

For a rigid 3D object, the dynamic properties consist in the object's ***tensor of inertia***. The tensor of inertia is a 3 by 3 matrix that characterizes the rotational inertia of the object about a fixed point in space, a major emphasis has been given to particularly in respect to the three principal moments (eigenvalues) and three principal directions (eigenvectors) that yield the tensor's geometric configuration, the inertia ellipsoid (Solomon & Turvey, 1988).

$$\begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{yx} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

where I_{xx}, I_{yy}, I_{zz} are the moment of inertias that quantify the torque needed to make a desired movement at a certain angular acceleration about a fixed rotational axis. It is one of *the three moments, namely the zeroth (mass), first (static moment) and second (moment* *of inertia)*, which are invariant over the variations in the forces brought to balance the object movement (Turvey & Carello, 2011). The inertia tensor depends on the object's mass distribution and thus on the shape of the objects. Assuming that the object density is uniform, this observation raises the question on whether people can perceive the shape of a rigid body from the interaction force when wielding it. In particular, researches on spatial length or mass estimation hypothesised that the perceptions of object dimensions (and other properties) of a wielded object has its basis in *the moments of the object's mass distribution*, for instance, the inertia tensor of the object about the wrist dictated the estimated length of the object.

Turvey and collaborators investigated the capacity of people to perceive the shape of an object via its inertia tensor, based on the hypothesis that the force and/or torque perception is based on the inertia tensor which depends on the spatial distribution of the object's mass (Turvey & Carello, 2011). Their seminal study focused on the estimation of the length of a stick by wielding it (Turvey et al., 1998). They found that people performed quite well at this task and people were able to perceive the variant torques of objects with equal mass but varied length, which depends on the position of the centre of mass with respect to hand, and the inertia force. In later studies, they investigated the capacity of people to identify the shape of a set of rectangular wooden objects: larger height than width, equal height with width, and smaller height than width. Participants wielded along the two dimensions sequentially and turned out to judge objects as being wider than they were high, as being higher than they were wide, and as being equal in height and width when that was indeed the case (Turvey & Carello, 2011).

In Turvey's (1996), length perception task of rods in fixed material and fixed diameter, the perceived length was found approximately a linear function of actual length. The fact that the perceived mass is not as equal as the actual mass, but is properly ordered and arbitrary, indicates that the perceived magnitudes are relatively ordered and within a marginal tolerance of the actual magnitudes (Prescott, Ahissar, & Izhikevich, 2016; Turvey, 1996).

4.1.3 Deformable objects

The characteristic of deformable objects is to change shape when a pressure or force is applied to it. In simple cases such as a spring, the force is proportional to the displacement

$$F = k\Delta x$$

where k corresponds to the stiffness. For soft objects, it also involves material properties such as their ***hardness or softness***.

Tan *et al.* (1995) looked at the role of maximum force as a specific component within terminal force cues in a relatively complex task of compliance discrimination, in which two plates were grasped between the thumb and the index finger and squeezed together along a linear track. Evidence showed that the maximum force is an important cue in the context of compliance discrimination (Tan, Durlach, Beauregard, & Srinivasan, 1995). When the mechanical work and terminal-force cues were dissociated with the compliance cues, compliance resolution was poorly relative to force and length resolution. People tend to use force cues and/or mechanical work cues whenever such cues are available, rather than on compliance values in compliance discrimination tasks.

4.1.4 Actuated articulated objects

As introduced in Section 1.4, a major difference between rigid bodies and articulated objects is that the dynamic properties of articulated objects change with linkage configuration. For instance, the apparent mass of articulated object is configuration-varying so that the force needed to move the object depends on the position of links. Another dynamic properties of linkage is to transmit forces generated from motor and this transmission is also affected by the configuration of the linkage. The enabling of joint motor produces an active force that can be passively perceived at the end-effector, or results in an increase in system stiffness. For two-DoF articulated objects, the magnitude and direction of the applied force depends on the joint torque in a complex manner.

In the next section, we formulate the position-dependent variant force characteristics of the articulated objects mathematically.

4.2 Section one - Mathematical modelling

This section presents the mathematical modelling of some of the dynamic properties of 2-DoF articulated system.

4.2.1 Static mapping

For 2-dof articulated object, the magnitude and direction of the interaction force at the end-effector depends on the joint torques and the joint configuration.

Let τ be the actual torques produced by the motors and F corresponds to the resulted force at the end-effector, then it can be shown (see Appendix B) that there is a direct relation between the joint torques and the end-effector force:

$$\tau = J^T \cdot F$$

where J is the Jacobian matrix

$$J(\theta_1, \theta_2) = \begin{bmatrix} -l_1 \cdot \sin\theta_1 - l_2 \cdot \sin(\theta_1 + \theta_2) & -l_2 \cdot \sin(\theta_1 + \theta_2) \\ l_1 \cdot \cos\theta_1 + l_2 \cdot \cos(\theta_1 + \theta_2) & l_2 \cdot \cos(\theta_1 + \theta_2) \end{bmatrix}$$

It is important to note that the Jacobian depends on the configuration (θ) of the device. Changing the configuration of the 2-DoF system simultaneously results in changes of the direction and magnitude of the end-effector force.

This equation can be easily inversed since the Jacobian matrix is square for a 2-dof planar system.

$$F = J^{-T} \cdot \tau$$

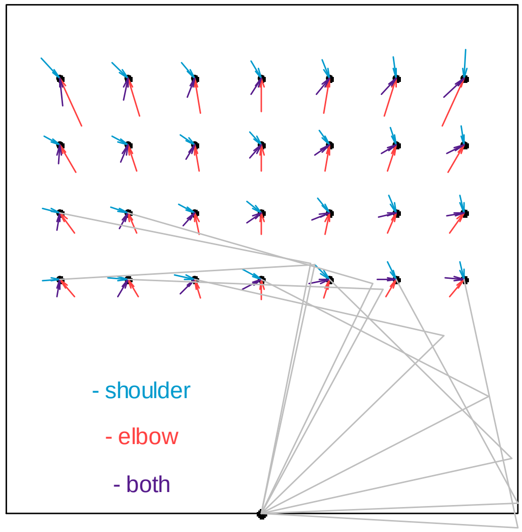


Figure 27. Three groups of force vectors at selected grid of location sites about the corresponding actuated shoulder joint, elbow joint, both joints motor-generated torque.

As an example, Figure 27 shows the force fields generated by the shoulder, the elbow and both motors respectively. Globally the force field is constant given a standard torque value, but position-dependent. The direction of the elbow-torque generated force is always towards the shoulder joint, and the magnitude of the force increases as the distance between the end-effector and the shoulder joint in the longitudinal direction increases. The direction of the shoulder-torque generated force is aligned with the second link.

Therefore a fundamental question raises in the aspect of perception: are people able to gain an internal model on the state (activated or deactivated) of the motors during the interaction with a 2-DoF articulated system? This question leads to a straightforward empirical hypothesis. If people can discriminate the force/torque produced from different motors, they should be able to extract the invariance/difference in the characteristics changes from the position-dependent force.

4.2.2 Dynamic modelling

Dynamic model is the relation between the applied forces/torques and structural properties in the motion of a robotic manipulator. In human-robot physical interaction, perceived force at the end-effector is not always equal to the applied force by the actuated object. When the velocity and/or acceleration of the movement is not constant, there's a movement-dependent discrepancy between the torque-related force and the force of measurement.

In an applied situation, the dynamic model of a manipulator may be affected by the elasticity in the mechanical structure, friction and other factors that are neglected in this analysis. In the derivation of the dynamic model, we consider the 2-dof system is composed of a series of connected rigid bodies.

Here we use the Euler-Lagrange approach for dynamic model of a planar 2-dof manipulator. Therefore, the Lagrangian equation is

$$\varphi = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q}, L = K(q,\dot{q}) - V(q)$$

where K is the kinetic energy and P is the potential energy function. φ is the external generalized torque performing work on q. In this case,

$$\varphi = \tau + J^T \cdot F_{ext}$$

Then, the dynamic model is obtained as

$$\varphi = \begin{bmatrix} M_1 + 2M_2\cos q_2 & \frac{2}{3}M_2 + M_2\cos q_2 \\ \frac{2}{3}M_2 + M_2\cos q_2 & \frac{2}{3}M_2 \end{bmatrix} \begin{bmatrix} \ddot{q_1} \\ \ddot{q_2} \end{bmatrix} + \begin{bmatrix} -M_2\sin q_2\,\dot{q_2} & -M_2\sin q_2\,(\dot{q_1} + \dot{q_2}) \\ M_2\sin q_2\,\dot{q_1} & 0 \end{bmatrix} \begin{bmatrix} \dot{q_1} \\ \dot{q_2} \end{bmatrix}$$

where $M_1 = \frac{1}{3}m_1 l_1^2 + \frac{4}{3}m_2 l_2^2$, and $M_2 = \frac{1}{2}m_2 l_2^2$.

The Lagragian equations can be written in matrix form as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} = \tau + J^T(q)F_{ext}$$

where $M(q)$ is the inertia matrix.

Apparent mass

Almost all studies to date have focused on the dynamic properties of ***rigid bodies***. For rigid objects, the dynamic properties are ***invariant*** under rotations about the origin. In the case of non-symmetric rigid body rotation over a fixed point, the centre of masses of rigid body is assumed to be located at a fixed point. In contrast, for articulated objects, the distribution of the mass depends on the position of the links. As a consequence of the mass distribution, dynamic properties of ***articulated objects*** depend on their ***configuration.***

The apparent mass is a quantity that measures the dynamic interaction of the articulated objects. The apparent mass defines the relation between the force applied on the end-effector and the resulting acceleration $F = M(q)a$, where $M, F, and\ a$ are the apparent mass, interaction force, and acceleration respectively. It is also well-known as an alternative way to express the mechanical impedance of the device.

In this section, we consider the apparent mass of a 2-link planar manipulator. For the 2-link manipulator, the direction and magnitude of interaction force depends on the configuration of the manipulator. Moreover, the direction of the acceleration is not necessarily aligned with the direction of the force. While the apparent mass is a simple scalar for a point mass object, the apparent mass of a 2-dof planar manipulator is a 2 by 2 matrix.

The inertia force is a critical component of dynamic force at the end-effector when moving the 2-DoF robotic arm. The endpoint inertia specifies a relationship between an external endpoint force and the endpoint acceleration. It can be represented by an ellipse, termed as ellipse of inertia (Me). The apparent mass depends on the point of application and direction of the impact force and on the body posture.

$$M = (J^{-1})^T \cdot I \cdot J^T$$

$$M_e = M \cdot M^T$$

where M is the inertia matrix, and J is the Jacobian matrix.

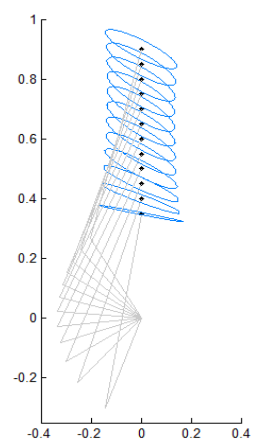


Figure 28. Ellipse of inertia of a two-link manipulator

Figure 28 shows an example of how the shape and axis lengths change along with the configuration of a two-link manipulator. When the same amount of force is applied at the end-effector, movement along the short axis of the ellipse allows a larger acceleration than movement along the long axis.

4.3 Section two- System design and development

4.3.1 Objective

The objective of this work is to develop a novel articulated manipulator made of two (or possibly) serially linked elements for the study of haptic perception in dynamic properties such as motor torques. To this end, a light, low-friction, and modular planar robot system for psychophysics perception study is developed and evaluated. This system offers a simple and reliable solution for weak force perception tasks.

4.3.2 Design specification

AirRob system is particularly designed for the study of weak force perception and discrimination. The aim of this system is to be used in investigating the human capability in perceiving the torque force from different sources generated from a robotic system.

A robotic manipulator is composed by an open kinematic chain, and its dynamic model is affected by several factors such as rigidity, friction, mass distribution. Minimizing the influence of non-linear effect or uncertain factors decreases the discrepancy between desired force and actual force in dynamic interaction. A fundamental objective is to improve the precision of the target generated force. Therefore, the requirements of the system development include high transparency and accuracy in control. Table 4. shows the general specifications of the actuated system. A modular system allows the users to change the properties such as the length or mass of each link rapidly with ease.

Table 4. Specific requirements on the robotic system development in the domain of psychophysical studies

	Transparency	Accuracy of control	Easy to change the properties
Requirements	Light Less friction	No lagging High precision	Dimensions Mass (inertia) Force (torque)

4.3.3 System characterization

Mechanical structure

The system is modularly designed to adjust the parameters to specific experimental conditions (for example, the number of links, the mass of each link, and the sources of force) in ease, and easily adapted to specific experimental parameters (e.g. torques about the motors).

Links of the robot arm The mechanical structure of the robot arm links is made of annular carbon fiber tubes, connected by a clamp to fasten the relative positions of two tubes. The outer and inner diameters of the tubes are 15.8*14mm and 18*16mm respectively. It is clearance fit to allow translational movement between the two tubes and ensure tight connection. The length of each link can be changed by sliding the two fitted tubes.

Joints of the robot arm The motor and encoder are embedded in the joint cover, which is 3D printed with ABS materials to minimize the weight.

Handle The handle has a cylindrical shape which can rotate around the central axis of the handle. It is designed to be easily manipulated by both human and robots.

Weight support The weight of joint is supported by mounting a roller ball/air bearing (S102501 flat round air bearing, NewWay) to avoid elastic deformation of the link and to minimize the friction force.

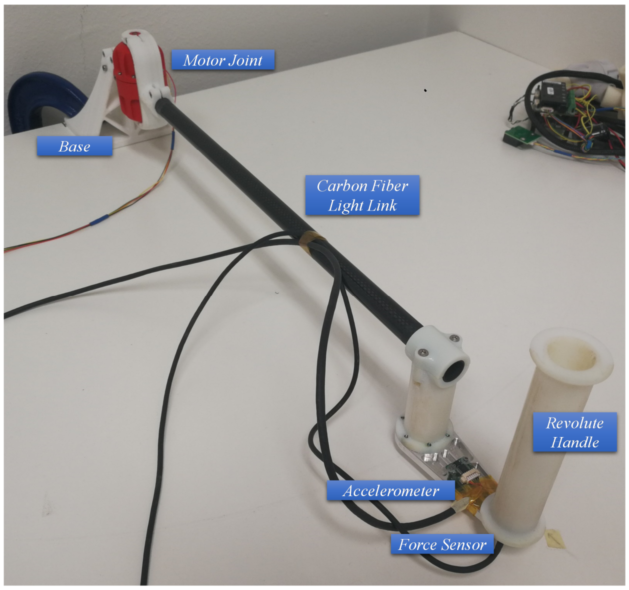
Electronic system

The setup consisted of a motor (QB0170XF Quantum frameless brushless servo motor, Allied Motion) control system commanded by the computer, an encoder (AS5245 programmable 360deg magnetic angle encoder, Austriamicrosystems) to measure the angular position of each joint, EMS and 2FOC boards developed by Electrical design laboratory in IIT for the control of encoders and motors, ATI force sensor (Nano 17) to measure the interaction force applied by the user, National Instrument (NI DAQ 6225) unit used for data acquisition and system synchronization.

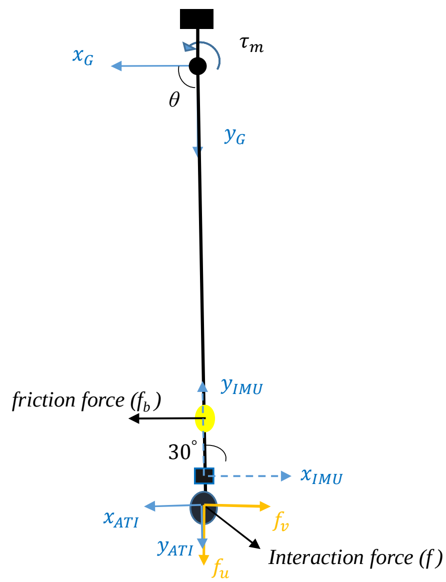
The software program is based on a Microsoft Visuo Studio 2015 C++ library for the control and acquisition of mechatronics system.

4.3.4 System development

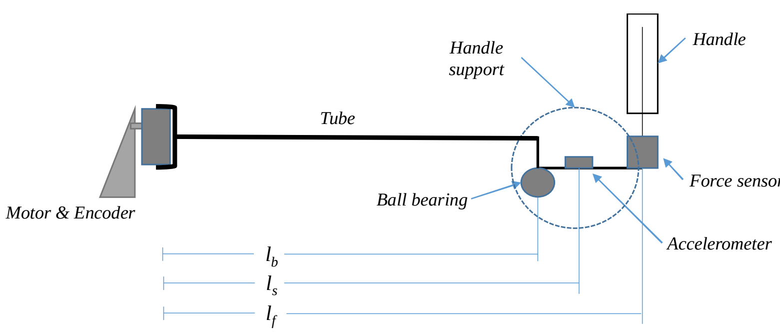
First prototype



(a) 1DOF mechanism



(b) Model of force coordinates



(c) Illustration of the structure of the 1-DoF mechanism

Figure 29. First prototype of the modular system

System parameter identification

The performance of the initially developed system is evaluated by measuring and estimating the force components (as shown in Figure 29). It is necessary to accelerate the object to estimate and/or measure its friction force. A first step is to evaluate a 1-DoF system has only one joint without actuator.

The unknown terms (including the inertia) can be identified from the force measured while moving the device. To estimate the componential forces from perceived force, a possible method is to use a multiple variable function on the motion of the device.

$$\tau = \beta_m \ddot{\theta} + \beta_c \frac{\dot{\theta}}{\|\dot{\theta}\|} + \beta_v \dot{\theta} + \beta_0$$

where θ refers to the angular position. The torque value is composed of the inertia force, Coulomb and viscous friction forces, and noise. The term $\beta_0$is expected to be very small. Note that the value of the Coulomb (β_c) and viscous (β_v) friction depend on the weight of the device and the pressure applied on the handle,

$$\beta_c = \beta_{c_0} + \beta_{c_1} f_p$$

$$\beta_v = \beta_{v_0} + \beta_{v_1} f_p$$

where f_p refers to the pressure force. The value of the coefficients β is the unknown parameters.

To evaluate the performance of the system, first we measured the interaction force to understand the friction produced by the ball bearing. The force sensor measured the interaction force f, which could be decomposed into a tangential (f_v) and radial (f_u) components. The ball bearing caused a friction force (f_b) that was aligned with the movement direction.

The equation of motion of the one degree of freedom device (assume the damping and stiffness coefficients are nearly close to 0) is

$$\tau_{ext} = I\ddot{\theta} + \tau_b$$

Where τ_{ext} is the torque that moves the device, I refers to the device inertia and τ_b is the friction torque due to the ball bearing. The torque τ_{ext} that moves the system comes from the interaction force

$$\tau_{ext} = l_f f_v$$

Note that the interaction force along the tangential direction f_v corresponds to the measured force: $f_v = -f_x$. The inertia I corresponds to the masses that are moving on the proximal side of the force sensor, i.e. the rotor of the motor, the carbon tube and the handle support part. The friction torque is related to the friction force

$$\tau_b = l_b f_b$$

The angular velocity and acceleration are measured by the encoded and accelerometer simultaneously. The force f_v and f_p are equal to the measurement from the – x and z axes of the force sensor respectively. Figure 30 shows the estimated components of force based on the proposed model in an acquisition of 20 seconds.

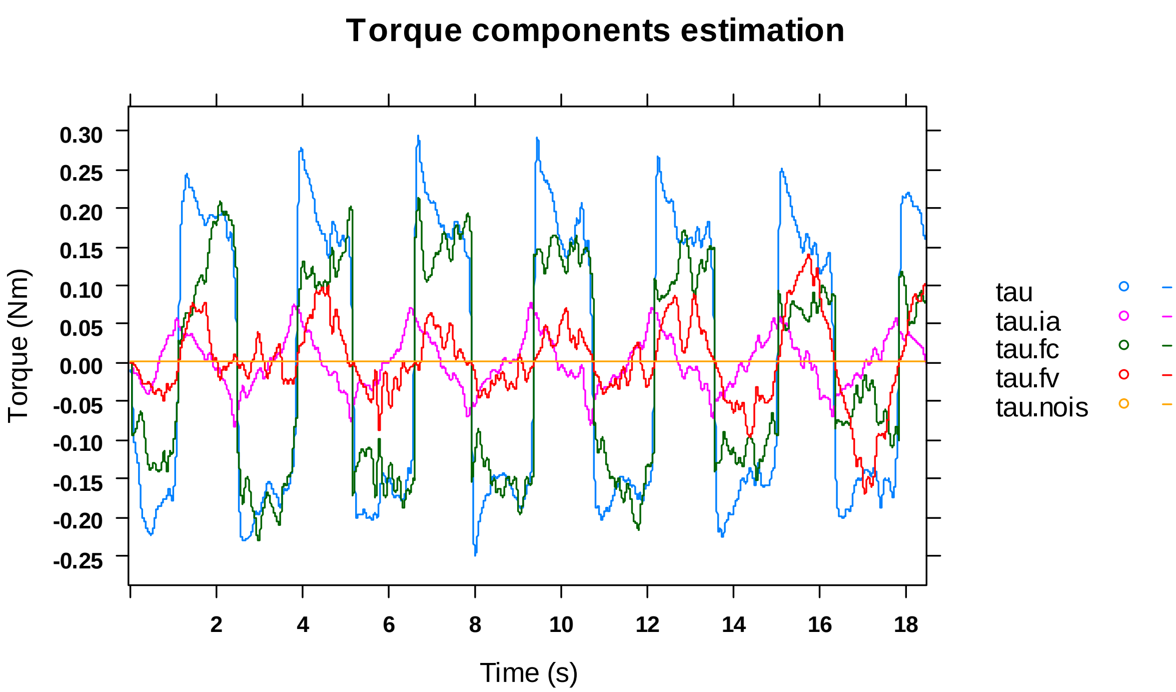


Figure 30. Components estimation on the interaction torque.

The parameters of the tangential force components are fitted based on the proposed model,

$$\tau = \beta_m \ddot{\theta} + \beta_c \frac{\dot{\theta}}{\|\dot{\theta}\|} + \beta_v \dot{\theta} + \beta_0$$

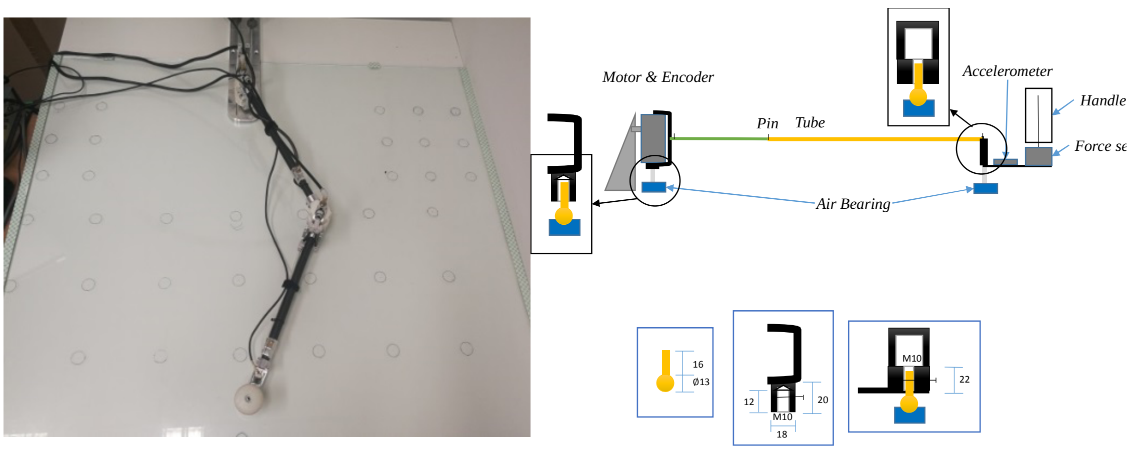
Then we have,

$\beta_m = 0.0124, \ \beta_0 = 0.0010$

The estimated inertia value 0.0124 $kg \cdot m^2$ was approximate to the theoretical value 0.015 $kg \cdot m^2$. The Coulomb friction force could reach 0.23N, and the viscous friction force was about 0.16N, which were considered large values of friction force in a weak force perception experiment.

To deal with this issue, we replaced the ball bearing with the air bearing to reduce the friction force and improve the transparency of the system.

Current prototype



(a) 2DoF setup platform (b) Mechanical structure of the system

Figure 31. Current development of the 2DoF system

Therefore, we upgrade the system to improve the performance by maximizing motor capability, reducing the force sensor signal noise to a possible minimum. A structural update is to replace the ball roller with the air bearing system, and some rapid prototyping parts are replaced by aluminium mechanisms (see Figure 31). The measured friction force with air bearings mounted under the joint and handle is less than 0.005N.

We would like to do the same system characterization measurement as introduced in the last subsection, but the friction forces turned out to be too weak which is out of the precision limit of the force sensor. Another issue is about the signal, too much interference to do when testing the static modelling of the system when the force sensor is on.

4.4 Section three – Pilot experiment

The goal is to investigate whether people can make use of specific complex force field produced by articulated object. The force perceived at the end-effector can be produced by either the shoulder joint motor or the elbow joint motor. To understand the origin of the torque-related force one needs to induce the system parameter from the perceived force at the handle in the method of inverse kinematics. And Jacobian matrix is a key element in the inverse reasoning process. Hence, the question is, can people have an internal representation based on kinematic and/or dynamic model that allows them to perceive the invariance in it?

4.4.1 Procedure

Subjects were sitting in front of the manipulation platform. They were explained linguistically the shoulder and elbow joints and the corresponding movement manually-controlled. Then subjects were instructed to hold the handle with little grip strength and move the end point of the system to understand how it feels like when moving the system without actuated motor control. The arm was at rest position hovering with elbow joint at 90° and the initial hand position was aligned with each participant's shoulder, to make it flexible for the upper limb movement when controlling the robotic device on the horizontal plane. The subjects were instructed to follow the instruction to start and stop movements for exploration.

The actuating status of the two motors are controlled to yield four different experimental conditions: a) the shoulder motor is actuated; b) the elbow motor is actuated; c) neither of the two motors is activated; d) both shoulder and elbow motors are producing standard torques. The amplitude of the motor torques are calculated and adjusted so that the magnitude of the end-point force remains at 0.05Nm.

After each trial of exploratory movement, the subject had to give feedback on whether one/both of the motors was activated, and which one(s) was the actuated motor(s).

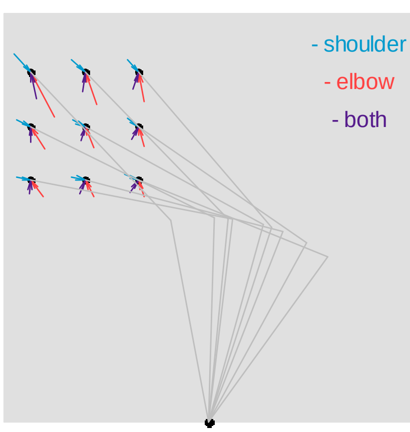
4.4.2 Results

Table 5. Responses from six subjects

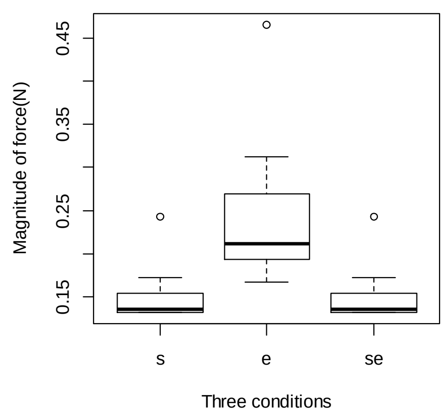
Force condition	Response				Successful rate (%)
	0	1	2	3	
0	59	5	4	4	81.94
1	5	57	3	7	79.17
2	3	10	33	26	45.83
3	2	3	48	19	26.39

The result showed that subjects had a good performance in recognizing the null-torque condition and torque generated by the first joint, but had difficulty in distinguish the torque generated by the elbow joint or both joints (see Table 5). Taking a close look on 2×2 matrix involving two experimental conditions, subjects don't make confusion when comparing shoulder and elbow joints, but confused when there's both joints actuated.

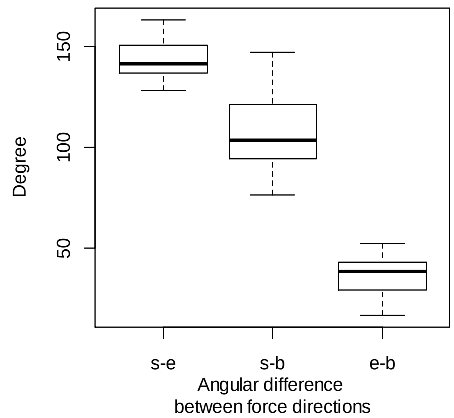
Figure 32 shows the mapping between the torque produced by the joints and the force at the end-effector. The length of the force vector represents the magnitude of the force and direction corresponding to the direction of the applied force. A 3×3 grid sites are selected within the given circular hand movement area to illustrate the force field.



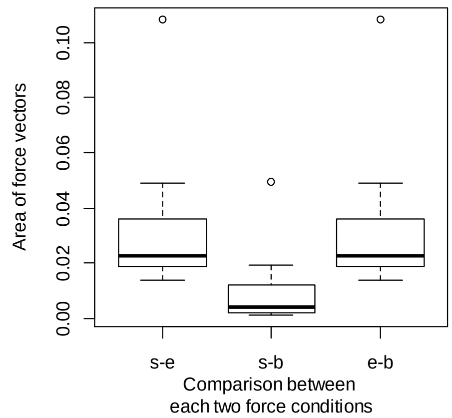
(a) Force field in the hand space



(b) Magnitude of force in the three conditions



(c) Difference in force directions between each paired condition



(d) Area between force vectors of each paired condition

Figure 32. Comparison in the produced force in three conditions

Componential analysis on the force vector shows that subjects' discrimination on torque origins may rely more on the force direction rather than the magnitude of the force, or the difference in the area formed by two force vectors.

4.4.3 Discussion

Results showed that subjects were able to discriminate the null force field and force generated by the shoulder joint at a weak force level (~0.15N). The evidence that they were able to induce the torque source of actuated joints from the perceived force indicated that either a Jacobian-related inverse model is involved in the internal model, or they are able to find a particular hand movement trajectory corresponding to specific torque-force transformation mapping.

Following the first hypothesis, Jacobian matrix is a part of the internal model which subjects have about the transformation between the hand perceived force and the motor torque. As a consequence, subjects should be able to detect the corresponding actuated motor if the force or difference between force vectors is noticeable. As indicated in the figure above, there's an obvious contrast in force vector between elbow joint and other conditions. A few studies have investigated the discrimination of the threshold related to the force direction, i.e. the minimum angle between two forces of the same magnitude. Yang *et al.* measured the discrimination threshold of haptic force direction during the hand movement (using PHANToM Omni haptic device). They revealed a mean difference threshold of force direction of 32°, which suggests that, in situations where the change of force direction is less than 32°, additional visual cues may be needed to facilitate awareness (Yang, Bischof, & Boulanger, 2008b). This is confirmed in a review of Ho *et al.* that the recommended force direction discrimination threshold for use in the design of haptic devices is on the order of 25-33° (Ho, Barbagli, Salisbury, & Spence, 2018). Yang *et al.* found that the hand-movement speed and the reference-force direction did not affect the perception of force direction (Yang et al., 2008b).

Some studies assessed the sensitivity to haptic force magnitude. In Allin *et al.*'s experiment (2002), subjects were asked to press against a virtual spring simulated by the PHANTOM TM device, while a tangential force is applier to the index finger's semi-circular trajectory. The study revealed a JND of approximately 10% (Allin et al., 2002). Yang *el al.* tested the force discrimination thresholds in the movement towards different directions, they found that the movement speed doesn't have a significant effect on the discrimination in force magnitude, but the perception of force magnitude was found to be affected by force direction. An oblique effect was found at a force direction of 45° with respect to the hand movement, as human perception of force magnitude is impaired (higher discrimination threshold) (Yang, Bischof, & Boulanger, 2008a). However, Yang found that when hand movement is involved the average JND is 33%, which is much higher than 10% reported by Allin (2002). To be more specific, the mean discrimination threshold for 0% direction is 0.49N, JND = 33%; while for 45% direction is 1:01N, JND = 67%, which is remarkably higher (Yang et al., 2008a).

In the present test, the difference between force magnitudes in the four conditions involved is much larger than 10% of the mean force produced by shoulder joint (the minimum among the three actuated motor conditions). The difference in mean value of the force direction between each two conditions is larger than 35°. Taken all together, observations indicated that a specific Jacobian matrix based representation is not embedded as a part of the internal model.

Further work will be focused on the hand trajectory of subject's exploration in the torque discrimination task.

Appendix B

In appendix B we presented an alternative method to formulate the end-effector force generated from the motor torques of 2-DoF system in the polar coordinates.

The control of robotic manipulators is commonly considered in a global or local Cartesian coordinates. However, for the human body motor control, a general idea has been being that the hand motor control is based on the shoulder-arm coordinates. In an active interaction, the robotic manipulator should be able to emulate the characteristics of the human body motor system. Therefore, we introduce a novel method to control and interpret a 2-DoF actuated mechanism in the polar coordinate system.

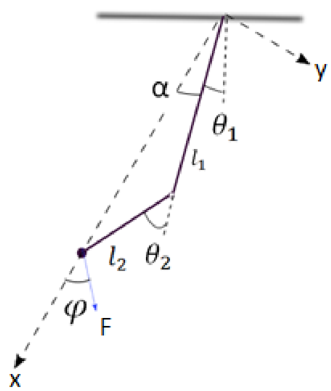


Figure 33. 2-DoF mechanism in local Cartesian coordinates.

A common method of specifying the joint space in terms of independent joint variables is to use the rotational angles in Cartesian coordinates q_i: (θ_1, θ_2). In the global coordinate, the position of end-effector $\vec{x}$ is

$$\begin{bmatrix} x_g \\ y_g \end{bmatrix} = \begin{bmatrix} l_1 \cdot \cos(\theta_1) + l_2 \cdot \cos(\theta_1 + \theta_2) \\ -l_1 \cdot \sin(\theta_1) - l_2 \cdot \sin(\theta_1 + \theta_2) \end{bmatrix}$$

the distance between the end-effector and the original of coordinate is:

$$d = \sqrt{{x_g}^2 + {y_g}^2} = \sqrt{{l_1}^2 + {l_2}^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\theta_2)}$$

According to the law of sines in trigonometry,

$$\frac{l_2}{\sin \alpha} = \frac{d}{\sin(\pi - \theta_2)}$$

Thus, $\alpha = \sin^{-1}(l_2 \cdot \sin\theta_2 / \sqrt{{l_1}^2 + {l_2}^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\theta_2)})$.

1. Jacobian matrix

We define the vector space spanned by the joint variables the joint space, and the vector space spanned by the end-effector location, the end-effector space.

1) Transformation between actuator space and end-effector space

In this derivation the end-effector space is expressed in a polar coordinates xi (r, phi), each point on the plane is determined by the distance from Pole O and the angle from Polar axis D. The position of the end-effector with radial coordinate and angular coordinate is expressed as $(d, \alpha + \theta_1)$.

$$\begin{bmatrix} r \\ \varphi \end{bmatrix} = \begin{bmatrix} d \\ \alpha + \theta_1 \end{bmatrix} = \begin{bmatrix} \sqrt{{l_1}^2 + {l_2}^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\theta_2)} \\ \theta_1 + \sin^{-1}(l_2 \cdot \sin\theta_2 / \sqrt{{l_1}^2 + {l_2}^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\theta_2)}) \end{bmatrix}$$

Then the time derivatives of r and φ, can be written as a function of $\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}$ as follows:

$$\begin{bmatrix} \dot{r} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{\partial r}{\partial \dot{\theta}_1} & \frac{\partial r}{\partial \dot{\theta}_2} \\ \frac{\partial \dot{\varphi}}{\partial \dot{\theta}_1} & \frac{\partial \dot{\varphi}}{\partial \dot{\theta}_2} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 0 & -l_1 \cdot l_2 \cdot sin(\theta_2)/d \\ 1 & ({l_2}^2 + l_1 \cdot l_2 \cdot cos(\theta_2))/d^2 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}$$

Then the Jacobian matrix that transforms the joint rates in the robotic actuator space(arm joint control) to the velocity state in the end-effector space is

$$J = \begin{bmatrix} 0 & -l_1 \cdot l_2 \cdot \sin(\theta_2)/d \\ 1 & ({l_2}^2 + l_1 \cdot l_2 \cdot \cos(\theta_2))/d^2 \end{bmatrix}$$

Hence the Jacobian matrix is a function of q2 and configuration dependent.

2) Velocity transformation between Cartesian coordinates and polar coordinates

$$\begin{cases} x = r \cdot \cos\varphi \\ y = r \cdot \sin\varphi \end{cases}$$

$$\dot{x} = \dot{x}(\varphi) = J_\varphi \cdot \dot{\varphi}$$

$$\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix} = \begin{bmatrix}\cos\varphi & -r\cdot\sin\varphi\\ \sin\varphi & r\cdot\cos\varphi\end{bmatrix}\cdot\begin{bmatrix}\dot{r}\\ \dot{\varphi}\end{bmatrix}$$

$$J_\varphi = \begin{bmatrix}\cos\varphi & -r\cdot\sin\varphi\\ \sin\varphi & r\cdot\cos\varphi\end{bmatrix}$$

2. Torque control

Applying the principle of virtual work to derive a transformation between the joint torques and end-effector forces, the virtual work, δW, done by all the active force is given by

$$\delta W = \tau^T\cdot\delta\theta - F^T\cdot\delta x$$

Substituting the virtual displacements related by the Jacobian matrix into the virtual work equation yields

$$\tau = J^T\cdot F$$

Where,

$$J^T = \begin{bmatrix}0 & 1\\ -l_1\cdot l_2\cdot sin(\theta_2)/d & ({l_2}^2 + l_1\cdot l_2\cdot cos(\theta_2))/d^2\end{bmatrix}$$

External force

$$\dot{x}^T\cdot F = \dot{\varphi}^T\cdot\mathcal{F}$$

Thus,

$$\mathcal{F} = {J_\varphi}^T\cdot F$$

Where,

$${J_\varphi}^T = \begin{bmatrix}\cos(\theta_1+\alpha) & \sin(\theta_1+\alpha)\\ -d\cdot\sin(\theta_1+\alpha) & d\cdot\cos(\theta_1+\alpha)\end{bmatrix}$$

F(F, β)

$$\mathcal{F} = {J_\varphi}^T\cdot F = \begin{bmatrix}\cos(\theta_1+\alpha) & \sin(\theta_1+\alpha)\\ -d\cdot\sin(\theta_1+\alpha) & d\cdot\cos(\theta_1+\alpha)\end{bmatrix}\cdot\begin{bmatrix}F\cdot\cos\beta\\ F\cdot\sin\beta\end{bmatrix}$$

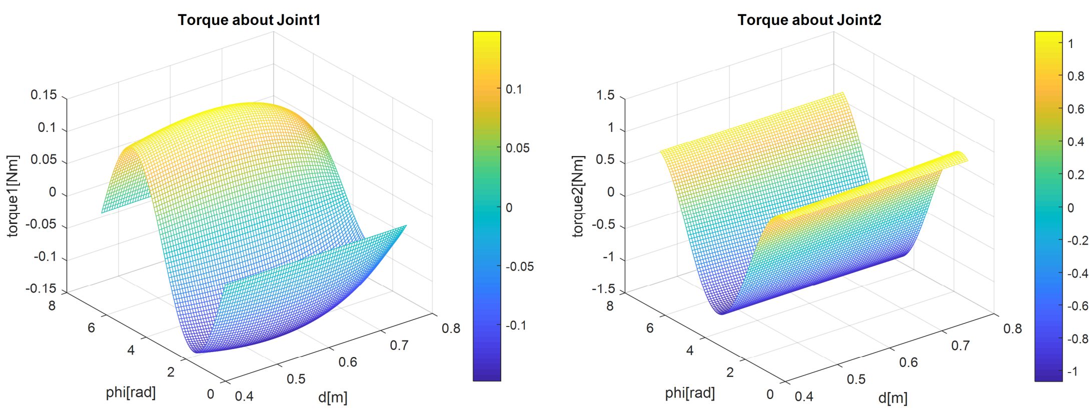
We define $\beta' = \beta - \alpha - \theta_1$, then

$$\mathcal{F} = \begin{bmatrix}\cos\beta'\\ d\cdot\sin\beta'\end{bmatrix}\cdot F$$

Since the vector of joint torques is denoted by $\tau = \begin{bmatrix}\tau_1 \\ \tau_2\end{bmatrix}$, and the end-effector force expressed as $\mathcal{F}(F,\beta) = \begin{bmatrix}\cos\beta' \\ d\cdot\sin\beta'\end{bmatrix}\cdot F$, and distance d remains the same in any coordinates, we conclude that $\tau = f(\theta_2, F, \beta)$

$$\begin{bmatrix}\boldsymbol{\tau_1} \\ \boldsymbol{\tau_2}\end{bmatrix} = \begin{bmatrix}0 & 1 \\ -l_1\cdot l_2\cdot sin(\theta_2)/d & ({l_2}^2 + l_1\cdot l_2\cdot cos(\theta_2))/d^2\end{bmatrix}\cdot\begin{bmatrix}\cos\beta' \\ d\cdot\sin\beta'\end{bmatrix}\cdot F$$

Simulation results are shown in the figure below (Figure 34). To generate 0.1N force at the end-effector, the relationship between the distance, external force direction, and the required torque produced from the shoulder and elbow motor are shown in figure (a) and (b) respectively.



(a) Torque about the shoulder Motor (b) Torque about the elbow Motor
Figure 34. Force field and motor torques mapping in static state

Chapter 5

General conclusions and recommendations for future work

This chapter summarizes the main conclusions regarding of the studies presented in this thesis, and suggests possible future work related to the present research.

5.1 General conclusions

This thesis investigates several aspects in the perception and control of articulated objects. It includes several haptic size discrimination experiments, visuo-motor control tasks, and the development of a high-transparency modular robotic system. The key findings and contributions are listed as follows:

- Observations showed that people are able to judge the size of elements (links) of articulated objects such as large-size pliers. They can make use of the various kinematic cues from the interaction movements. Different from features of the haptic size discrimination with rigid objects, the objects are commonly fixed on the table, in the plier experiment, we found that lifting the object improved the discrimination performance and facilitated bimanual integration to happen. A follow-up with wooden box and box-shaped actuated apparatus added supporting evidence to the observation that free manipulation facilitates bimanual integration.

  It is interesting to note that physical coupling of an object being manipulated with two hands is possibly a key factor of bimanual integration in the domain of motor control. The brain coordinates the action of the two hands to control the object movement to achieve a certain level of dexterity.

  The fact that we observed in the bimanual integration with wooden boxes in both grounded and free conditions could be due to the contextual effect of mixed conditions and familiarity with manipulating rigid objects like boxes. It is possible that familiar objects are easier to infer their shapes or sizes because a top-down process is triggered in bimanual integration.

- We found that seeing the dynamic structure of the mechanism can help to predict the movement of one part of a 2-DoF linkage when moving another part of the mechanism. The fact that an better average performance in pre-vision conditions than non-vision conditions indicated that subject were able to use the visual information about the linkage to predict the trajectory of the cursor, so that the performance is as good as the condition in absence of any transformation.

The short-time exposure of visual representation of the mechanisms helped improve the performance in the reaching task, but not as much as the continuous visual feedback. It is probably due to the fact that pre-visual feedback of the mechanism enabled the metal reasoning and planning on the movement thus improved the performance, and the continuous visual information of the mechanism helped to correct the error during the movement. Therefore, we can conclude that visual feedback of the mechanisms dynamic structure improves reaching performance in both planning and execution phases.

For the pure rotational conditions, the difficulty increased from 0° to 90° degree (in both clockwise and counterclockwise direction), and a tendency of decrease towards higher degree of rotation (180°).

Another observation is that the complexity (in terms of the number of linkages) of the mechanisms didn’t determine the difficulty of the task and the visual effect in motor learning. Instead, we have found a specific parameter of the parallelogram mechanism that related to the task performance. The strength of the visual effect was related to the distance between the two parallel rods of the parallelogram. The observation with parallelograms suggested that the visual effect is most helpful: the mechanical linkage is easy to interpret visually, for instance, when the linkage has only two links or, for parallelograms, the two horizontal and parallel links are close.

- We developed and evaluated a light, low-friction, modular planar robot system (AirRob) with variable link lengths and masses actuated by motors directly placed at the joints for psychophysics perception study. This system offers a simple and reliable solution for weak force perception tasks.

  Results showed that people can make use of specific complex force field produced by articulated object to discriminate the torque produced by different joints.

Subjects were able to discriminate the null force field and force generated from the shoulder joint at a weak force level (~0.15N).

In the present study, the difference between force magnitudes in the four conditions involved is much larger than 10% of the mean force produced by the shoulder joint (the minimum among the three actuated motor conditions). The difference in mean value of the force direction between every two conditions is larger than 35°. Taken all together, observations indicated that a specific Jacobian matrix based representation is not embedded as a part of the internal model.

5.2 Future work

- In the first study we found that adding constrains to the objects has a significant effect on bimanual integration. It would be interesting to find out whether seeing the box or the mere knowledge that one is lifting a box is sufficient for bimanual integration. Another question needed to be answered is that whether free manipulation is necessary to trigger bimanual integration with less familiar objects like pliers.
- It is important to find out whether the visual effect of the mechanism is related to a specific transformation characteristic, and how the hand movement is planned or corrected from the beginning of the movement based on the visual information.
- There is evidence that tool use can immediately change the limit between the near and far space and the body schema. It would be interesting to find out that whether use of such complex-mapping tool leads to an immediate shortening of the limb length representations. In addition, brain imaging techniques will be involved to study whether vision of linkages in visuo-motor control recruits the ventro-dosal system.
- The evidence showed that subjects were able to induce the source of torque produced by different actuated joints from the perceived force. Further work will be focused on the hand trajectory of subjects in the torque discrimination task, to find out whether there is a mapping between a particular hand movement trajectory and specific torque-force transformation.

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