Perception, 2011, volume 40, pages 1081 – 1103

doi:10.1068/p6879

Perceptual weight judgments when viewing one's own and others' movements under minimalist conditions of visual presentation

Malika Auvray¶§, Thomas Hoellinger, Sylvain Hanneton, Agnes Roby-Brami
Laboratory of Neurophysics and Physiology, CNRS UMR 8119, University Paris Descartes, Paris, France; § Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur, CNRS UPR 3251, Orsay, France; e-mail: malika@malika-auvray.com
Received 30 November 2010, in revised form 18 August 2011

Abstract. Across five experiments, we investigated the parameters involved in the observation and in the execution of the action of lifting an object. The observers were shown minimal information on movements, consisting of either the working-point displacement only (ie two points representing the hand and object) or additional configural information on the kinematics of the trunk, shoulder, arm, forearm, and hand, joined by a stick diagram. Furthermore, displays showed either a participant's own movements or those of another person, when different weights were lifted. The participants' task was to estimate the weight of the lifted objects. The results revealed that, although overall performance was not dependent on the visual conditions (working point versus stick diagram) or ownership conditions (self versus other), the kinematic cues used to perform the task differed as a function of these conditions. In addition, the kinematic parameters relevant for action observation did not match those relevant for action execution. This was confirmed in experiments by using artificially altered movement samples, where the variations in critical kinematic variables were manipulated separately or in combination. We discuss the implications of these results for the roles of motor simulation and visual analysis in action observation.

1 Introduction

1.1 *Sensitivity to human movements: The motor-simulation and visual-analysis accounts*

When observing other people, we are able to understand and interpret their actions in a seemingly effortless fashion. This ability relies not only on the perception of social cues or physical appearance, but it also depends on sensitivity to human movement. For instance, Johansson's (1973) point-light technique isolates the kinematic cues from any information about the form by reducing the movements of the body to the motion of just a few point-lights attached to the major joints of the body. However, even with such reduced kinematic information, participants are able to recognise lifted weights (eg Bingham 1987, 1993; Runeson and Frykholm 1981, 1983; Shim and Carlton 1997), the gender of a person (Barclay et al 1978; Cutting 1978; Kozlowski and Cutting 1977; Pollick et al 2005), the identity of a walker (Cutting and Kozlowski 1977; Jacobs et al 2004), expectations and deceptive intents (Runeson and Frykholm 1983), the elasticity of a surface (Stoffregen and Flynn 1993), and even a dancer's emotional state (Brownlow et al 1997; Dittrich et al 1996).

Two main hypotheses have been put forward to account for our understanding of others' actions. The first one posits that our ability to perform the same movements facilitates perception (eg Wilson 2001). In this case, the sensitivity to human movement relies on a functional link between the visual and the motor systems (eg Viviani and Stucchi 1992). The second hypothesis suggests that our understanding of others' actions can be performed through a purely visual analysis (eg Johansson 1973).

The first class of theories, which emphasises perception – action coupling, follows James' ideomotor principle (James 1890, volume II, page 526) according to which imagining an action will create a tendency to carry it out. The actual execution of the

---

¶ Address for correspondence: LIMSI, BP 133, 91403 Orsay, Cedex, France.

action will occur if there are no simultaneous antagonistic mental images. This principle has more recently been developed into the theory of action simulation in neuroscience (Dokic and Proust 2002; Gallese and Goldman 1998) and the theory of event coding, which involves a common coding of sensory and motor codes (eg Hommel et al 2001). According to the theories that emphasise perception – action coupling, there is a functional equivalence of perceptual and action representations; perceptual representations contribute to action and, conversely, action representations contribute to perception. More precisely, actions are coded in terms of the resulting perceptual events and, conversely, whenever an observer perceives events resulting from an action, his corresponding motor codes are activated (motor-simulation hypothesis). This occurs to the degree that the perceived events are linked with actions in the individual's repertoire (eg Prinz 1997). Following on from this view, the visual analysis of another person's actions is influenced by the observer's motor system. As a consequence, visual sensitivity to human movement will depend on whether or not the movement is consistent with the biomechanical constraints of the human body.

Neurophysiological evidence provides support for common mechanisms underlying action observation and action execution. In particular, Rizzolatti and his colleagues have reported the existence of neurons that fire both when a monkey carries out goal-directed actions such as grasping a peanut, and when the monkey watches the experimenter perform the same action (eg Gallese et al 1996; Rizzolatti et al 2001; see also Rizzolatti and Craighero 2004). Note that, according to Fogassi and his colleagues (2005), the mirror neuron system in monkeys seems to be more related to the goal of the action than to the precise details of action execution. In humans, common motor areas are active both when planning and performing actions and when perceiving the actions of others (Blakemore and Decety 2001; Decety and Grèzes 1999). However, such activation of the motor system during action observation only occurs when observers watch biomechanically possible movements (Stevens et al 2000).

In addition, the motor-simulation hypothesis can be divided into two main versions: a strong version proposes that there is direct matching between the perception and action systems (see Gallese et al 2004; Rizzolatti et al 2001; see also Jacob 2009 for a critical review). It follows that matching the kinematic properties of perception and action is critical. A weaker version suggests that, although there is activation of the motor system in response to the observation of an action, the kinematic details of the action need not be encoded (eg see Fogassi et al 2005).

An alternative view is that the recognition of human movement is based on a purely visual analysis, without the need of any motor simulation (eg Bülthoff et al 1998; Giese and Poggio 2003). Visual sensitivity to human movement is due to the fact that observers have more visual experience with human motion than with any other type of dynamic event. In particular, according to Johansson (1973), our high level of performance with point-light displays is due to extensive prior visual experience with perceiving these types of movement. As a consequence, performance in movement recognition should depend on the frequency with which particular movements were previously observed. This account explains our greater sensitivity to biological than to mechanical motion not by a link between perception and action but as resulting from greater visual experience with human motion. Behavioural support for the hypothesis of movement recognition through visual analysis comes from experiments in which the participants rate the extent to which a three-dimensional point-light walker looks human. Performance depends critically on whether participants view the walker from an unusual or from a common (ie sagittal) point of view (Bülthoff et al 1998).

1.2 *Perceptual weight judgments*

Perceptual weight judgments provide a way to investigate the extent to which there is a link between action observation and motor performance. Indeed, previous studies on perceptual weight judgments have investigated the correspondence between performed and observed movements using a succession of static pictures (eg Valenti and Costall 1997), full form videos (eg Hamilton et al 2007), and point-light displays (eg Shim and Carlton 1997). However, in order to understand more specifically which specific kinematic cues used in perceptual weight judgments are and whether or not they match the performed actions of lifting, we propose to use simplified graphical animations of the action of lifting that allow better control of the amount of information displayed.

In particular, in the study reported here, we investigated three main questions. First, we assessed how much and what kind of properties are extracted in the observed movement. Following on from a motor-simulation hypothesis, this question relates to the amount of observed movement taken into account in the simulation. More precisely, we investigated whether observers can perceive one kinetic property of the object (its weight) from the kinematics of the hand and object alone (eg displacement and velocity) or whether they also use the topological characteristics of the posture (and, more particularly, of the upper limb configuration) reflecting the relative motion of body segments. Scully and Newell (1985), following on from the findings of Runeson and Frykholm's study (1981) on lifting motion, argue that observers perceive the relative motion of body parts. Thus, carrying different weights can lead to different displacement speeds but also to different inter-joint coordination. For instance, when lifting an object using the whole body, the involvement and timing of the limbs and spine rotations vary with the weight of the object (eg Scholtz et al 1995). In addition, although this parameter has not been directly investigated, it is likely that people adapt their trunk and upper-limb motor coordination when lifting heavier objects (ie they increase trunk bending and/or limit elbow extension). The argument that posture influences perceptual weight judgments finds support in our ability to infer the weight of objects from static pictures (eg see Valenti and Costall 1997). If indeed people use the topological characteristics of the posture to estimate the weight of an object being lifted, then observers will have better performance when being shown such information on posture along with movements of the hand and object (ie in the latter case, the display is limited to the displacement of the task-related points or 'working-points'). In order to test this prediction in experiment 1 we displayed recordings of an actor lifting different weights. We measured the ability of participants to make perceptual weight judgments when only the working-point displacement was shown and when the kinematics of the trunk, shoulder, arm, forearm, and hand, joined by a stick diagram, were shown.

The second question investigated here relates to the perception of our own versus others' movements. Are we better at recognising the kinetic properties of objects when observing our own movements? In addition, do we extract the same information when we observe the movements of other people as compared with when we observe our own movements? The hypothesis of a close connection between perception and action making for better performance when observing our own movements has been suggested by Gibson (1979) and re-developed in the theory of event coding (eg Hommel et al 2001). According to this view, as we have a motor-learning history for a specific task and as we have knowledge of our own anatomical constraints, our perception – action system is optimally tuned for the observation of our own actions. This occurs either because we have a greater tendency to carry out exactly the same action, or because we better anticipate the effects of the perceived action due to a similar action simulated internally during observation. In order to investigate this hypothesis, in experiment 2 we recorded the movements of twelve participants lifting objects with different weights. Subsequently, in experiment 3, we displayed to the participants simplified representations of their own movements and simplified representations of another participant's movements. This allowed us to investigate whether accuracy in perceptual weight judgments is better when viewing our own or another person's movements.

The third question examined here is whether or not the cues relevant for weight categorisation during action observation are the same as the variables varying consistently with weight during action execution. Hamilton et al (2007) investigated this question by varying the duration of four key phases of the action of lifting an object (reach, grasp, lift, and place). The authors found that, during action observation, the lifting-time parameter was most critical for perceptual weight judgments. On the other hand, during action execution, that is when analysing the natural movement of lifting, the authors found that the duration of the grip is the one that is the most sensitive to the weight of an object. The authors concluded that the optimal cues differ between performed and observed lifting movements. However, other parameters, aside from the duration of the different phases, might also be relevant. These other parameters include the velocity of the phases, the maximal lift velocity (Shim and Carlton 1997), and the maximal vertical acceleration of the object. In experiment 2 we analysed a data set from twelve participants lifting an object to establish the correlations between variance in weight and variance in kinematic parameters (such as the mean acceleration). Subsequently, experiment 3 investigated which parameters modify observers' perceptual weight judgments. Finally, experiments 4 and 5 investigated the most relevant parameters for action observation by altering the key components of the lifting action in the graphical animations. Overall, the study reveals whether or not parameters used during action execution match those used for perceptual judgments during action observation.

2 Experiment 1. Type of minimal information necessary for perceptual weight judgments

The aim of experiment 1 was to determine the amount of kinematic information necessary for action recognition: do the observers need to see the displacement of the working point only, or do they need to see the kinematics of the trunk, shoulder, arm, forearm, hand, and object? In order to investigate this question, we recorded the movements of an actor lifting objects of different weights. We then created graphical animations which displayed the displacement of the working points only (ie limited to two points representing the hand and object) and graphical animations consisting of a stick diagram which represented the trunk, shoulder, arm, forearm, hand, and object. These simplified representations of the action of lifting an object were then displayed from side view to participants who had to rank the estimated weights on a scale.

2.1 *Methods*

2.1.1 *Movement recordings.* Five black opaque glasses with an identical appearance (8 cm height, 7 cm diameter) but different weights were prepared. The glasses weighed 200, 500, 800, 1100, and 1400 g, respectively, different amounts of lead having been added inside each glass. Each participant's movement was recorded by a motion star system (ascension technology, 86 Hz frequency; static accuracy position: 0.76 cm; rms static accuracy orientation: 0.5 deg rms at 1.52 m range). To avoid interference with the measurement system, all metallic objects and electromagnetic sources were removed from the experimental room. One electromagnetic marker was placed on a lid used for the five glasses and five other markers were placed on the participant's body in the following locations: the middle part of the sternum, the acromion process, the upper third of the humerus, and on the dorsum of the hand at the level of the third metacarpal bone.

An additional marker was used to record the position of different anatomical body landmarks at the start of the experiment in order to construct the stick diagram based on each participant's anatomy. In short, the trunk and upper limb were represented by geometrical shapes delimited by bony landmarks digitised during a preliminary procedure (see Hanneton et al 2011 for further details). The thorax is defined by the processus xiphoideus, incisura jugularis, and processus spinosis of C7 and T8; the scapula by the angulus acromialis, trigonum spinae, and angulus inferior; the upper arm by the medial epicondylus, lateral epicondylus, and the glenohumeral rotation centre (computed from passive circumduction movements); the lower arm by medial and lateral epicondylus and the styloid processes. The three-dimensional position of each target was also recorded with the additional marker. The participant was fitted with noise-cancelling headphones and Plato liquid-crystal glasses that prevented him seeing the experimenter placing the glasses on the table in front of him during in-between trials. He was not told how many glasses were used or their weight. The participant started each trial with his right hand placed on his chest. When the glass he has to manipulate was revealed to him (by the opening of the Plato glasses), he was instructed to grasp and lift the glass with his right hand in order to place it on a shelf located 20 cm beyond and 18 cm above the starting point. The five glasses were presented 15 times each in a random order, so that the participant was not aware of the weight of the glass before lifting it.(1)

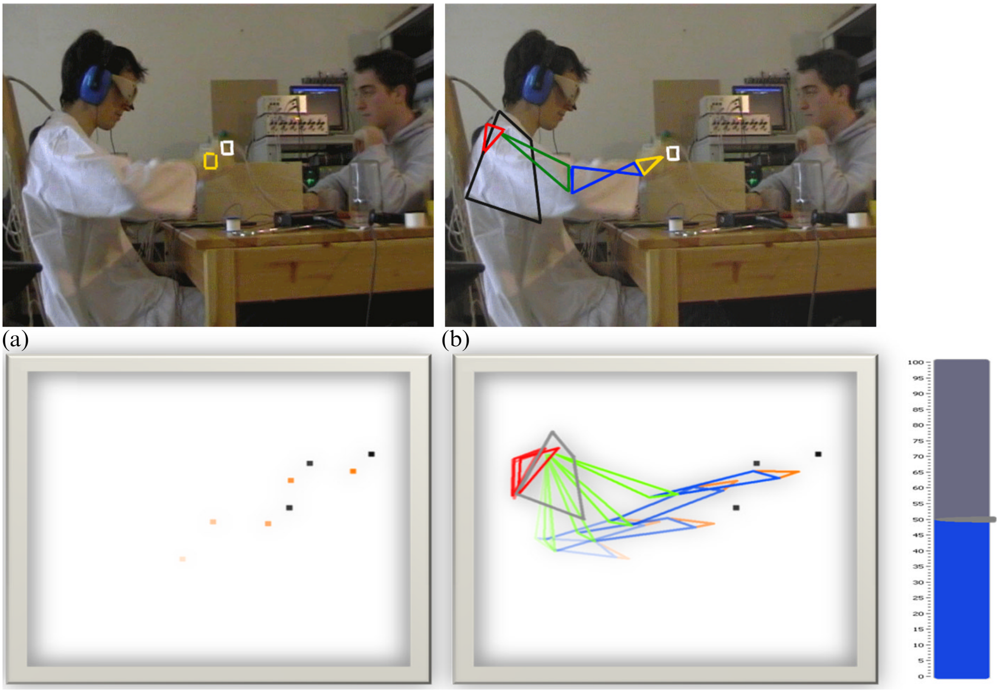
2.1.2 *Movement displays.* From the set of the movement recordings, the first three trials for each glass were removed and five recorded movements for each of the five glasses were selected randomly. Then, graphical animations were created for each selected movement which displayed either the displacement of only two points representing the hand and the object (working-point representation) or, in addition, the animations representing the trunk, shoulder, arm, forearm, and hand (stick-diagram representation, see figure 1). The animations were presented using Labview software.

2.1.3 *Participants.* Fourteen participants (seven females and seven males, mean age of 32.3 years) took part in this experiment which lasted approximately 40 min. In this experiment and all those reported here the participants had normal or corrected-to-normal vision and they were naive to the hypotheses under investigation. All the experiments were performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

2.1.4 *Materials and procedure.* Before the start of the experiment, the participants were given the opportunity to lift two visually identical glasses with weights of 200 and 1400 g (the lightest and the heaviest glasses used in the movement recordings). The participants were then shown one animation for each of these two glasses and for the two conditions of stimulus visualisation (working point and stick diagram). They were told that these two weights corresponded respectively to 10% and 90% of the possible weights. The participants were then told that they would be shown a set of animations and that,

---

(1) Preliminary recordings were conducted on two participants performing the same task but in blocked conditions of object presentation (each of the five different glasses was presented 15 times successively). Movement analysis revealed that participants' posture was more influenced by the order and number of repetitions of the carried objects than by the weight of the object. More precisely, the participants' posture becomes more and more bent during the experiment and this effect was greater than the influence of the objects' weight on posture. In addition, similarly to what has been shown previously under blocked conditions of weight presentation, the kinematics of the reach phase (Atkeson and Hollerbach 1985) and the kinematics of the lift phase (Gordon et al 1991; Johansson and Westling 1988) converged toward similar profiles, independently of the object's weight. Thus, in order to increase the distinctness of the different objects' weights, in all the experiments reported here we only used movement samples recorded in the random condition of object presentation.



(a) (b)

(c) (d)

Figure 1. [In colour online, see http://dx.doi.org/10.1068/p6879] Picture of the experimental setup used for the movement recordings in experiments 1 and 2. The added geometrical forms show the two conditions of visualisation presented to the observers during the perceptual weight judgment task: working point (a) and stick diagram (b). The bottom part shows the displays viewed by the participants when the working point (c) and the stick diagram (d) are in movement; on the right is represented the scale used by participants to give their response.

after each animation, a visual-analogical scale would be presented to them on the computer screen so that they could rank the estimated weights using the computer's mouse (the scale had 100 points; by default the cursor appeared in the middle). The participants completed ten practice trials for each of the two conditions of stimulus visualisation.

The participants then completed two experimental conditions of visualisation (working point and stick diagram) in two separate sessions whose order was counterbalanced across participants. Each session included five recorded lifts for each of the five weights, and each recording was viewed three times with the participants completing 150 trials in total. Within each session, the trials were presented in a random order, ie the order of presentation of the trials for the observers was not the same as the order in which the actor lifted the different weights. The ranking responses were non-speeded, but the participants had to give a response for every trial. No feedback was given regarding the accuracy of the participants' responses.

2.2 *Results*

An ANOVA performed on the participants' responses with the factors visualisation (working point versus stick diagram) and weight (five levels) revealed a significant main effect of weight ($F_{4,52} = 34.40$, $p < 0.0001$), no significant effect of visualisation ($F_{1,13} = 1.59$, $p = 0.23$), and a near-significant interaction between these two factors ($F_{4,52} = 2.38$, $p = 0.06$). A Duncan a-posteriori test on the weight factor revealed significant differences between 200 g and all the other weights (all ps < 0.001), between 500 and 1400 g ($p < 0.05$), and between 800 and 1400 g ($p < 0.01$). As shown in figure 2,

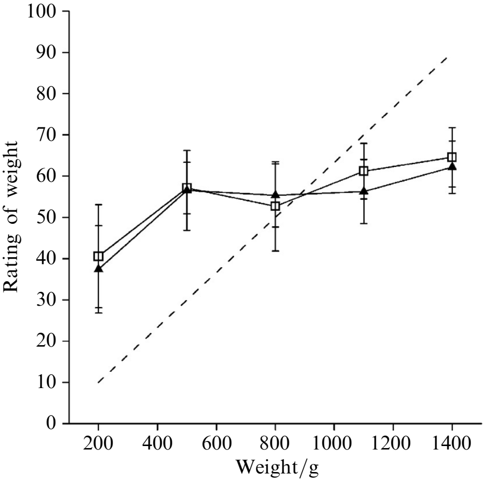


Figure 2. Participants' mean responses in the perceptual weight judgment task of experiment 1 as a function of the two conditions of visualisation: working point (black triangles) and stick diagram (white squares). Weights were computed in percentages of possible object weights, ie 200, 500, 800, 1100, and 1400 g corresponded respectively to 10, 30, 50, 70, and 90% on the response scale. The error bars represent ±1 SEM.

the observers overestimated the weights under 800 g and underestimated the weights over 800 g. This result is consistent with previous studies on the perception of lifted weights (eg Bingham 1987).

2.3 *Discussion*

The main result to emerge from the analysis of experiment 1 was that the participants were able to perform the perceptual weight judgment task even in the minimalist conditions of visual presentation used in this experiment. Indeed, their rankings of the weights seen in the graphical animations varied in correspondence with changes in the weight carried by the actor. This was particularly obvious for the lightest weight that was ranked as being lighter than all the other weights. However, the participant's performance was the same in the working-point and in the stick-diagram conditions. This result suggests that more precise kinematic details, that is the representation of the trunk, arm, and shoulder in addition to the hand and object does not facilitate action recognition. This result seems to contradict a strong motor-simulation hypothesis according to which all the kinematic aspects of an observed movement are taken into account in the simulation, whereas a weaker version would propose that there is a motor representation of the goals of the action but its kinematic details need not be encoded. It should be mentioned that such absence of any use of the changes in posture in order to determine the objects' weight does not confirm previous results from Valenti and Costall (1997) whose participants were able to infer objects' weight from static pictures, nor the results of Runeson and Frykholm's study (1981) according to which observers perceive the relative motion of body parts thanks to movement coordination. However, these two studies used heavier objects (which consisted of heavy boxes ranging from 1 kg up to 31 kg depending on the experimental conditions) which might have induced more pronounced changes in posture and thereby better cues to infer the weight of objects.

Alternatively, the other hypothesis that can be put forward in order to explain the absence of differences between the working-point and the stick-diagram conditions found in our experiment is that observers use configural information in addition to the working-point displacement for movements that are highly familiar to them. For instance, the participants in Bülthoff et al's (1998) study recognised more easily a point-light walker when viewed from a usual rather than from an unusual point of view. If familiarity with movements (whether it is a visual or a motor familiarity) indeed plays a role in movement recognition, then a subsequent prediction (tested in experiments 2 and 3) is that observers will use differently the configural information displayed to them when viewing their own movements and someone else's movements.

---

3 Experiment 2. Kinematic parameters varying with weight during action execution

In experiment 2, we recorded the movements of a larger set of participants lifting the same five objects that were used in experiment 1. In addition to replicating the results of experiment 1 with a larger number of actors, the aim of these additional recordings was twofold. First, these recordings were used in experiment 3 in order to investigate whether the participants were better at estimating weights when they viewed their own movements rather than when they viewed another participant performing the same action. Second, these recordings were used in order to establish the correlations between variance in weight and variance in several kinematic parameters in order to investigate whether or not the kinematic parameters that vary during action execution are the same as those used as reliable cues during action observation.

3.1 *Methods*

3.1.1 *Participants, materials, and procedure.* Twelve participants (four females and eight males, mean age of 28.7 years) participated in this experiment which took approximately 1 h to complete. The materials and procedure were the same as those described for the movement recordings of experiment 1.

3.1.2 *Movement analyses.* The motion star data give the successive positions of the sensors that were placed on the object and on a participant's hand. These successive positions were subsequently filtered with a Gaussian filter and the velocity was computed by a derivation of the positions as a function of time. The vertical velocity profile of the hand and object movements were used to delimit the successive phases of the action which can be decomposed into a fast upward phase of the hand, then a slower descent toward the object, followed by an upward movement of the hand lifting the object. The reach phase begins at the start of the hand movement (when its vertical velocity rises above 0.05 m s^{-1}) and ends at the onset of the hand's descent (when its vertical velocity decreases below 0.05 m s^{-1}). The grasp phase begins at this moment and ends at the onset of the object's lifting (when the vertical velocity of the object rises above 0.05 m s^{-1}). The maximal height of the object ($H_{\max}$) and its maximal velocity ($V_{\max}$) were computed together with the times at which they occurred. The lift phase lasts from the beginning of the movement of the object until the object reaches its maximal height. The duration of the lift was measured from the onset of lifting until the object reaches its $H_{\max}$. It was divided into an initial acceleration whose duration was measured from the onset of the object's lifting until the object reached its maximal velocity, at $V_{\max}$ time, and a subsequent deceleration (between $V_{\max}$ time and $H_{\max}$ time). The mean upward acceleration during the lift was measured by dividing $V_{\max}$ by the duration of the acceleration phase (from the onset of lifting until $V_{\max}$ time). The lift phase is followed by a slower place phase which lasts from the object's peak height until the end of the movement, as the box is put on the shelf.

3.2 *Results*

3.2.1 *Kinematic analyses.* The analyses focused on the following dependent variables: duration of the movement phases (reach, grasp, lift acceleration, lift deceleration, and place), maximal height of the object, maximal velocity, and mean lift acceleration. The means of the fifteen movements performed by each participant with each weight were computed. An analysis of covariance (ANCOVA) was conducted (ie with the weight as a cofactor) in order to investigate on which kinematic variables the linear trend of the weight has an influence (see figure 3). The results revealed that the duration of the grasp phase increased significantly with weight increase ($F_{1,58} = 27.82$, $p < 0.0001$) (figure 3a). The duration of the lift acceleration also increased significantly with weight increase ($F_{1,58} = 15.71$, $p < 0.001$) (figure 3b). The duration of the reach phase did not vary significantly with weight ($F_{1,58} < 1$, ns), nor did the duration

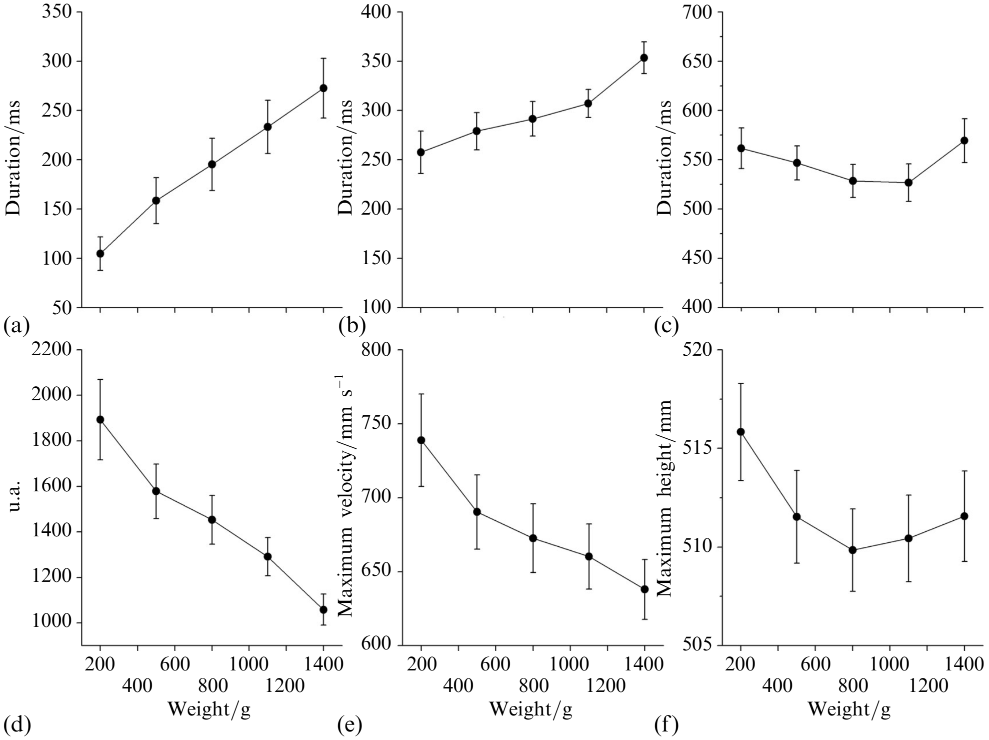


Figure 3. Variation of the kinematic variables with the weight of the object. (a) Duration of grasp phase; (b) duration of acceleration during lift; (c) duration of place phase; (d) mean acceleration; (e) maximum velocity; and (f) maximum height. The circles on the graphics represent the group average (twelve participants) and the error bars represent the standard error of the mean (means of 15 movements for each of the twelve participants).

of the lift deceleration phase ($F_{1,58} < 1$, ns), nor the duration of the place phase ($F_{1,58} = 0.005$, ns) (figure 3c). The mean acceleration during lift decreased significantly with weight increase ($F_{1,58} = 29.0$, $p < 0.0001$) (figure 3d) as well as the maximal velocity of the lift ($F_{1,58} = 9.2$, $p < 0.01$) (figure 3e). The maximal height of the object during the lift phase did not vary significantly with weight ($F_{1,58} = 1.8$, ns) (figure 3f). Note that the lightest weight was lifted 0.5 cm (±SE of 0.04 cm) higher than the other weights (Student's *t*-test, $p < 0.05$ after pooling the 500 – 1400 g weights).

3.3 *Discussion*

The results of experiment 2 are consistent with previous studies which have shown that an increase in object weight results in a prolongation of the grasping action (Brouwer et al 2006; Eastough and Edwards 2007; Gentilucci 2002; Weir et al 1991) consistently with the duration required for the building of the grip – load force coordination before lifting the object (Johansson and Westling 1984, 1988). In addition, the results revealed that, during the lift phase, the weight did not influence significantly the maximal height, except for the lightest weight, which was lifted higher than the others. It should be mentioned that this slight but consistent overshoot when lifting the lightest object might explain why it was scored proportionally lighter than all the other objects in experiment 1. The weight tended to decrease the maximal velocity of lifting, consistent with the results of Brouwer and his colleagues (2006) and Eastough and Edwards (2007) who found that increasing the object's weight induced a significant decrease in the velocity of lifting.

The results also revealed a significant effect of weight on the acceleration while lifting which decreased with increasing object weight. However, the amount of variation of the acceleration (less than twice as low) remained relatively limited compared with the large variations of the lifted weights (the heaviest object being seven times the weight of the lightest object). From these results, the prediction can be made that the variables related to the timing of hand – object relationships (the duration of the grasp and lift acceleration phases) and the kinematics of the object during lift (in particular the acceleration) should convey sufficient information for the perceptual weight judgment task, even when the graphical animation is limited to the displacement of the hand and object.

4 Experiment 3. Action observation: Viewing one's own versus others' movements

Previous studies suggested that participants perform better when observing an action that they previously performed rather than when observing other people performing the same action (eg Loula et al 2005). In particular, better performance for observers' own movements has been shown for predicting the landing position of a dart (Knoblich and Flach 2001) and for predicting the future course of handwriting trajectories (Knoblich et al 2002; see also Knoblich and Flach 2003, for a review). With respect to the perception of weights, it has been shown that, when watching movies of oneself and of someone else lifting boxes of various weights, temporal differences in premotor cortex activity differentiate one's own actions from the actions of others (Grèzes et al 2004).

The aim of experiment 3 was to investigate from a behavioural point of view whether participants are better in a perceptual weight judgment task after viewing their own movements rather than after viewing another participant's movements under minimalist conditions of stimulus presentation. In addition, the aim of experiment 3 was to investigate whether observers use the same cues when observing their own movements and someone else's movements. To do so, we repeated the comparison between the stick-diagram and working-point displays despite the lack of an effect found in experiment 1. Indeed, we supposed that, in the case of the recognition of someone's own movements, a more detailed display involving the trunk and upper limb configurations could improve performance. Finally, following on from experiment 1, in experiment 3 we further investigated whether perceptual weight judgments rely upon the kinematic variables that vary consistently with weight. The converse hypothesis is that observers may use other cues, despite their lack of biomechanical reliability.

4.1 *Methods*

4.1.1 *Participants, materials, and procedure.* The same twelve participants that took part in experiment 2 completed experiment 3. The materials and procedure were the same as those reported for the perceptual part of experiment 1 with the following exceptions. From the set of the movements' recordings of each participant that took part in experiment 2, the first 2 trials for each weight were removed and 10 recorded lifts for each of the five weights were selected randomly. The participants viewed both their own movements ('self' condition) and the movements of another participant who completed experiment 2 ('other' condition). This selection was done randomly, but in such a way that all the participants of experiment 2 served once in each condition and in such a way that the participants viewed the movements of another participant of the same gender. In addition, as in experiment 1, the participants completed two conditions of visualisation (working point and stick diagram) in two separate blocks of trials. The order of presentation of the two conditions of ownership (self versus others' movements) and of visualisation (working point versus stick diagram) was counterbalanced across participants. As in experiment 1, in each block, the order of presentation of the trials was randomised (ie the trials were not viewed in the same order as they were performed during movements' recordings). Each session included 10 recorded lifts for each of the five weights with the participants completing 200 trials in total. At the end of the experimental session, we told the participants that they had viewed their own movements and the movements recorded on another participant. We then asked them to determine which session corresponded to their own movements.

4.2 *Results*

4.2.1 *Main effects of ownership and visualisation.* An ANOVA performed on the participants' responses with the factors ownership (self versus others), visualisation (working point versus stick diagram), and weight (five levels) revealed a significant main effect of weight ($F_{4,44} = 60.83$, $p < 0.0001$), no significant effect of visualisation ($F_{1,11} < 1$, ns), ownership ($F_{1,11} < 1$, ns), nor any significant interaction between these factors. A Duncan a-posteriori test on the weight factor revealed significant differences between all the conditions of weight (all ps < 0.01). It should be mentioned that only five participants out of twelve recognised their own movements when they were asked which session corresponded to their movements and which one corresponded to someone else's movements.

4.2.2 *Relationships between the kinematic parameters and perceptual weight judgments. Simple regression analyses.* Simple regression analyses were conducted in order to determine the respective influences of the weight and of several kinematic variables individually on the response. These analyses were performed on sets of sixty values (twelve participants and five levels of weight). Simple regression of the response as a function of weight showed that the weight explained around half of the variance of the response and this amount was similar in the four experimental conditions (figure 4, grey bars, and table 1, left column). Some of the kinematic variables also explained a part of the variance on the response given as a function of the four experimental conditions (see table 1).

4.2.3 *Relationships between the kinematic parameters and perceptual weight judgments. Multiple regression analyses.* Multiple regression analyses (stepwise regression analysis, with automatic exclusion of variables by the default procedure of the SPSS software) were subsequently performed. The independent variables involved in this analysis were the kinematic variables of table 1, except the maximal velocity which was omitted since it is equal to the mean acceleration multiplied by the duration of lift and therefore it could not be included in a linear model.

The regression of the weight as a function of the kinematic variables was conducted in order to analyse those variables that convey information related to weight (action execution, right part of figure 4). The results showed that the information on weight

Table 1. Proportion of the variance of the perceptual weight judgments (adjusted r^2) explained by the weight (left column) and by the different kinematic variables considered separately, for the two conditions of ownership: self and other, and for the two conditions of visualisation: working point (WP) and stick diagram (SD). The different kinematic variables are respectively: duration (D) of the reach, grasp, acceleration (acc), deceleration (decel) and place phases, maximal height ($H_{\max}$), maximal velocity ($V_{\max}$), and mean acceleration (acc) during lift. The significant values are given in black bold characters, the non-significant values are in parentheses.

	Weight	D reach	D grasp	D acc	D decel	D place	$H_{\max}$	$V_{\max}$	Mean acc
WP—self	**0.49**	–	**0.14**	**0.30**	–	–	(0.02)	**0.28**	**0.45**
SD—self	**0.57**	(0.02)	**0.25**	**0.25**	–	–	–	**0.18**	**0.36**
WP—other	**0.53**	(0.03)	**0.27**	**0.31**	**0.07**	(0.01)	(0.03)	**0.37**	**0.43**
SD—other	**0.49**	–	**0.05**	**0.11**	–	(0.01)	**0.14**	**0.07**	**0.17**

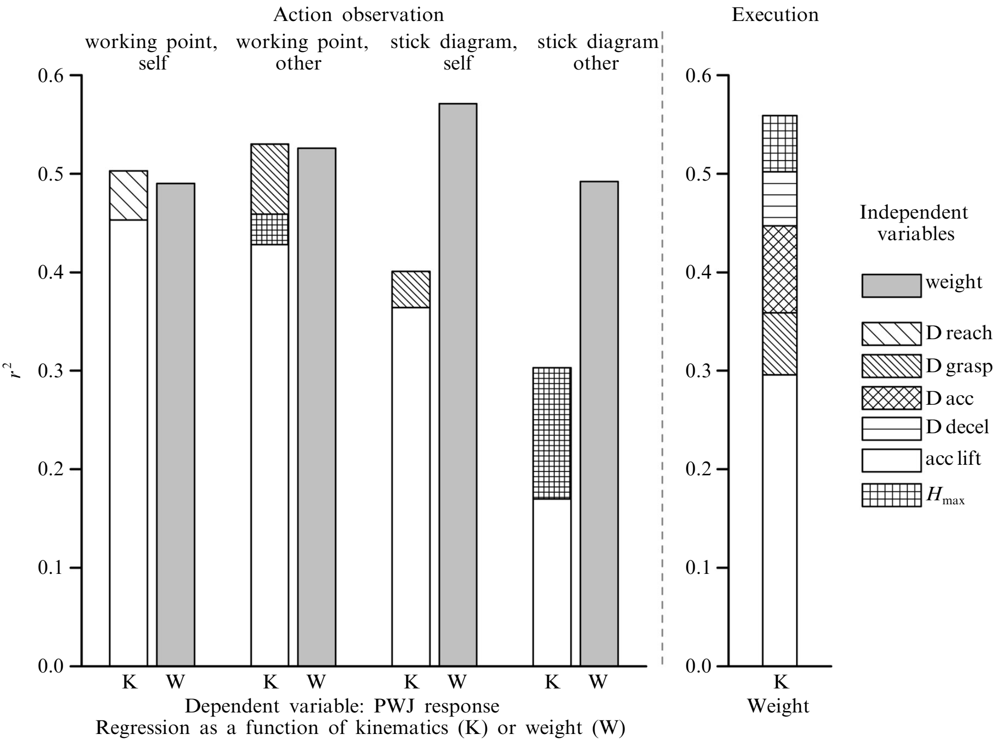


Figure 4. Percentage of variance at simple and multiple regressions (adjusted r^2) during action execution and for the four conditions of action observation. (a) Action observation. The grey histograms (W) represent the percentage of variance of the response explained by the weight in the four conditions. The combined histograms (K) represent the percentage of cumulated variance in the perceptual weight judgment responses explained by the kinematic variables in the multiple regression. (b) Action execution. The combined histogram (K) represents the percentage of cumulated variance in weight (ie accounting for the information on weight) explained by the kinematic variables in the multiple regression.

was at first strongly dependent on the acceleration during lift (adjusted $r^2 = 0.29$). The durations of grasp, lift acceleration, lift deceleration, and $H_{\max}$ also contributed for a cumulated amount of 56% of the variance (adjusted $r^2 = 0.56$).

The regression of the response as a function of the kinematic variables (action observation, left part of figure 4) revealed that, taken together, the kinematic parameters explain a similar amount of cumulated variance of the response in the working-point–self (52%) and working-point – other (53%) conditions, but less for the stick-diagram – self (40%) and even less for the stick-diagram – other conditions (30%).

In addition, this analysis revealed differences in the kinematic parameters contributing to the regression as a function of the conditions of visualisation and ownership. The value of the mean acceleration during lift was the only parameter to enter in the regression for the four conditions and always explained the greater amount of variance whatever the condition. In the working-point – self condition, acceleration during lift explained 45.3% of the variance and only the duration of the reach phase was additionally involved in the regression (for an additional 5.8%). In the working-point – other condition, in addition to the mean acceleration during lift (42.8%), the response also depended on the duration of the grasp phase (7.1%) and on maximal height (3.1%). In the stick-diagram – self condition, the responses depended significantly on acceleration during lift (36.4%) and on the duration of the grasp phase (for an additional 3.7%). In the stick-diagram – other condition, the responses depended on the mean acceleration (17%, which is less than for the three other conditions) and on maximal height (13%). Finally, it should be mentioned that, whereas the mean acceleration was involved in the regression in all the conditions of action observation, it represents a relatively small part of the information on weight during action execution (29%). In addition, the small number of kinematic variables influencing the response in each condition of action observation contrasts with the fact that, during action execution, the information on weight depended on information about the five kinematic variables.

Surprisingly, the multiple-regression analysis suggests that the duration of the lift does not bring information on weight, nor explain a part of the perceptual weight judgment responses. This can be explained by the fact that the correlation between the duration of lift and the weight ($r = 0.42$) is dependent on the correlation between the mean acceleration and the weight ($r = 0.55$). Indeed, partial correlation analysis showed that the correlation coefficient between the duration of lift and the weight was reversed when computed for a constant lift acceleration (partial correlation coefficient $r = -0.26$).

4.3 *Discussion*

In experiment 3, the participants performed a perceptual weight judgment task when viewing their own movements and the movements performed by another participant. It should be mentioned here that in this experiment we chose to display the movements of only one other participant instead of a set of movements taken randomly from all the participants, and we also chose to display the two conditions (self versus others' movements) in two separate sessions. This was done in order to avoid errors due to the successive perception of movements performed by different lifters. Indeed, Shim et al (2004) found that the participants in their study overestimated the weights lifted by the weakest lifter and underestimated the weights lifted by the strongest lifter. Thus, the observation of a lift performed by a strong lifter might influence the judgment on a subsequent lift performed by a weak lifter (and conversely). In addition, observers are better at estimating the lifter's produced effort than the actual weight lifted (Shim et al 2004). As a consequence, we hypothesised that the observers' performance as well as their confidence in their judgment would be better if they were shown and made aware that a series of lifts was performed by the same lifter.

Experiment 3 confirms, with a larger number of actors, the result of experiment 1, and in particular the possibility to make perceptual weight judgments from the visual observation of gestures. In addition, the first main result to emerge from the analysis of experiment 3 was that participants' raw performance was the same in the two conditions of ownership (self versus others' movements). Thus, contrary to our predictions, viewing our own movements does not improve performance. In addition, with respect to the comparison between the two conditions of visualisation, the participants' mean error was the same in the working-point and in the stick-diagram conditions (as in experiment 1), and this was the case both when viewing one's own and others' movements.

The second main result to emerge from the analysis of experiment 3 relates to the relationships between the kinematic parameters and perceptual weight judgments. Although there were no significant overall differences in global performance between the conditions of visualisation and ownership, the parameters used to perform the task were not the same for the four experimental conditions (see the Results section). In addition, the results revealed that the parameters that were the most relevant for action execution are not the same as the ones used during action observation. The mean acceleration contributed most of the variance both for action observation and for action execution. However, the other parameters that also played a part in the regression on action observation differed greatly as a function of the conditions and never included all the parameters involved in action execution.

It should be mentioned that the lack of a significant difference in overall performance between the different conditions of visualisation and ownership cannot be entirely attributed to the setup itself that could be thought to lack precise information. Indeed, the participants are sensitive to different kinematic variables depending on the conditions. This tends to suggest that performance is less due to a lack of sensitivity to these variables than to limitations in the attentional processes that are required to perform the task. As the observers cannot take into account all the parameters on the perceived weight (despite being able to process them), they do not simply use all the available information displayed. On the contrary, some parameters are privileged to the detriment of others and these differ as a function of the conditions.

In the two working-point conditions, the total amount of variance explained by the kinematic variables is roughly similar to the amount of variance explained by the weight. This suggests that some of these kinematic variables are sufficient to give an account on the information used for perceptual weight judgments. In the working-point – self condition, the participants relied mainly on the acceleration during the lift phase; in the other conditions they also used information linked to the duration of the grasp phase and maximum height. On the other hand, in the stick-diagram condition, the total amount of variance explained by the kinematic variables is much less than the amount of variance explained by the weight. This suggests that the participants used additional parameters linked to the global posture and/or displacement of the trunk and upper limbs (which were not quantified in the present study) when viewing the stick-diagram condition. In addition, the fact that the stick diagram does not improve overall performance in the self condition, as well as the fact that there are differences in the stick-diagram condition between viewing one's own and others' movements might be due to the involvement of an unnatural point of view in the latter case. After all, we never see our own shoulder blade. On the contrary, the working-point visualisation remains natural in the self condition: although it was registered in profile, the trajectory would not have been very different if the hand had had a trajectory starting from a lateral position toward the centre of the working space in front of the eyes.

5 Experiment 4. The role of the duration of the four phases of prehension (reach, grasp, lift, and place) on perceptual weight judgments

The results of experiment 3 revealed that, in order to make their perceptual weight judgments, the participants relied most on the mean acceleration during the lift phase plus to some extent the duration of the grasp and place phases, but they did not use the duration of the lift phase. Experiment 4 was conducted in order to further investigate the role of the duration of the four phases of the prehension movement (reach, grasp, lift, and place). It should be mentioned that our minimal display allows reconstructing a set of artificial movements by varying the phase durations while keeping the fundamental characteristics of smoothness of the trajectory and velocity profile of natural movements.

5.1 *Methods*

5.1.1 *Construction of the set of modified movements.* A mean movement was taken as a reference. This movement was chosen among the movements performed by one participant lifting the median weight (800 g) in experiment 2. The criterion for choosing the reference movement was that its kinematic variables were equal to the means of the rest of the group. For this experiment, we focused on the working-point display. The trajectories of the hand and object during this chosen movement were then altered by signal-processing methods (spline interpolation, offset) in order to obtain variations in the duration of the reach, grasp, lift, and place phases, without altering the maximal height of the object during lift. The durations were modified independently for each phase in order to take 60, 80, 100, 120, and 140% of the value of the reference movement (ie 16 altered movement samples in addition to 4 times the reference movement).

The trajectory and velocity profiles obtained by this method were regular and retained the global smoothness of the reference movement. The kinematics of the altered movements were quantified in order to determine the accuracy of the modifications. In all the cases, the durations of the modified phases fell within ±2% of the objective with less than 2% of unwanted modifications of the other phases. As expected, the acceleration during lift was altered by the modification of lift duration without modification of the height. The acceleration during lift was increased to reach respectively 246.9% and 135.6% of the value of the reference movement when the duration of the lift was decreased to 60% and 80% of the value of the reference movement. Similarly, it was decreased to 62.3% and 44.9% of the value of the reference movement when the duration of the lift was increased to reach 120% and 140% of the reference movement.

5.1.2 *Participants, materials, and procedure.* Twelve participants (three females and nine males, mean age of 30.4 years) participated in this experiment which took approximately 40 min to complete.

The materials and procedure were as follows: the participants viewed only the movements corresponding to the working-point displacement (see the left part of figure 1). Each session included 10 movements for each of the 5 durations of the 4 phases (which were modified independently) with the participants completing 200 trials in total. Prior to the experimental session, the participants were given 40 practice trials, so that they could see the variety of movements twice and thereby adjust their own relative scale. As in experiments 1 and 2, the participants had to rank on an analogical 100-point scale the estimated weights.

5.2 *Results*

Unlike the previous experiments reported here, experiment 4 could not directly evaluate performance on perceptual weight judgments, since the movements were synthetic. It was thus only possible to analyse the influence of the different kinematic variables involved in the displayed movements on the participants' responses. As shown in figure 5, perceptual weight judgment responses were significantly correlated with the duration of the lift ($r = 0.691$, $p < 0.01$, $n = 60$); however, they were not correlated with the duration of the reach, grasp, or place phases ($r = -0.031$, $r = 0.046$, and $r = 0.028$, respectively, ns). The responses were significantly inversely correlated with the acceleration during lift ($r = -0.737$, $p < 0.01$).

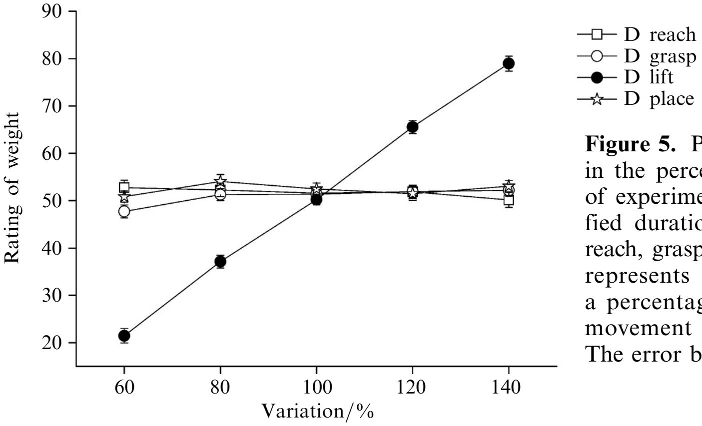


Figure 5. Participants' mean responses in the perceptual weight judgment task of experiment 4, with artificially modified durations of the following phases: reach, grasp, lift, and place. The abscissa represents the durations computed as a percentage of those of the reference movement (with average kinematics). The error bars represent ±1 SEM.

Multiple regression analyses (stepwise regression analysis, with automatic exclusion of variables by the default procedure of the SPSS software) were performed on the perceptual weight judgment responses with the duration of the 4 phases and the mean acceleration during lift as independent variables. This analysis showed that 63.7% of the variance of the response was explained by the kinematics of the displayed movements: 54% is due to the acceleration during lift with, in addition, a small contribution (9.6%) of the duration of the lift. An individual analysis of the results could be performed, since all the participants viewed the same samples. For ten out of the twelve participants, the duration of acceleration and lift were the main variables explaining together between 72% and 94% of the variance of the responses. Another participant responded only as a function of lift duration (59% of the variance explained). The last one responded as a function of acceleration and duration of the reach, lift, and grasp phases (for a total of 76% of the variance explained).

5.3 *Discussion*

The results of experiment 4 revealed that the duration of the lift phase influences perceptual weight judgments, whereas the durations of the reach, grasp, and place phases have no effect on the participants' performance. This result is consistent with previous studies (Bingham 1987; Hamilton et al 2007; Runeson and Frykholm 1981) according to which the kinematic pattern related to the lift is the major source of information used in order to infer objects' weight. This result is, in particular, consistent with those of Shim and Carlton's (1997) study which showed no significant difference between a group of participants observing only the lift and a group observing the lift and other types of movements.

Importantly, the results and, in particular, the multiple regression analyses suggest that the effect of lift duration could be due to a modification of the acceleration during lift. This hypothesis has never been examined in previous studies and consequently experiment 5 was designed to investigate this point.

6 Experiment 5. The relative contribution of lift duration, acceleration, and amplitude on perceptual weight judgments

Experiment 5 was designed so as to further investigate the relative contributions of lift duration and lift acceleration on perceptual weight judgments by varying the amplitude of the lifting movement. In addition, the aim of the experiment was to further analyse the effect of the maximal height of the lift which contributed to weight judgments in several conditions of experiment 3. Experiment 5 was performed with a set of artificial movements built in order to vary simultaneously the following three parameters: lift duration, lift acceleration, and lift amplitude (maximal height).

6.1 *Methods*

6.1.1 *Construction of the set of modified movements.* The artificial movements were constructed by the same methods as in experiment 4, with the same natural movement used as reference. The modifications combined simultaneous variations of the duration and amplitude of the lift (which could take 90, 100, 110, and 120% of the reference value for lift duration and 96, 100, 104, and 108% of the reference value for lift amplitude). We obtained a sample of 16 artificial movements with regular trajectories and smooth velocity profiles (see figure 6a). The quantitative verifications confirmed that all the durations fell within ±1% of the objective and the amplitudes fell within ±0.2% of the objective. As expected, the acceleration scaled regularly both as a function of lift duration and lift amplitude (see figure 6b). In the whole sample, the resulting acceleration varied between 66% (for the 120% duration and 96% amplitude) and 140% (for the 90% duration and 108% amplitude) of the reference value.

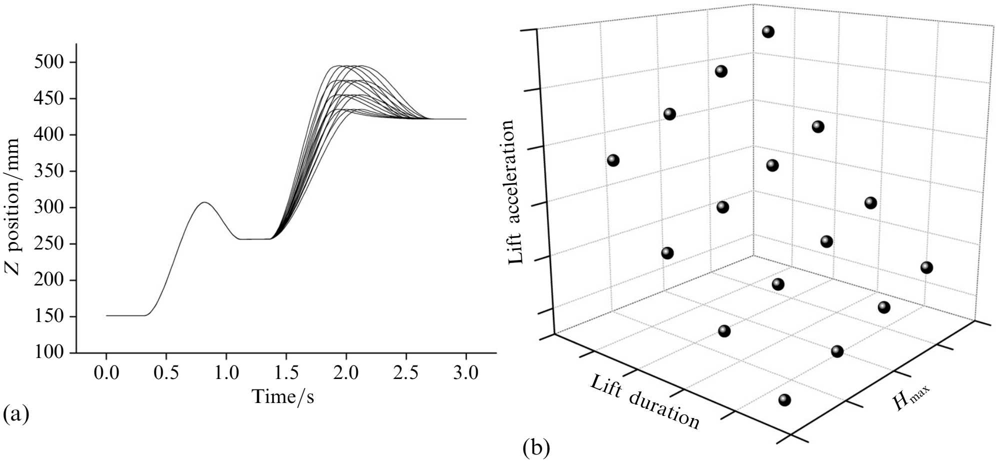


Figure 6. (a) Modified vertical trajectories of the hand used for experiment 5. The trajectories were simultaneously modified both in duration of the lift (90, 100, 110, and 120% of the reference duration) and in maximal height (90, 100, 110, and 120% of the reference height). The trajectories of the object were also modified and follow those of the hand. (b) Graphic of the values of lift acceleration obtained for the 16 artificial movements shown in (a) as a function of lift duration and height.

6.1.2 *Participants, materials, and procedure.* Twelve participants (four females and eight males, mean age of 33.2 years) participated in this experiment which took approximately 40 min to complete. The materials and procedure were the same as those reported for experiment 4. Each session included 12 repetitions for each of the 16 movements with the participants completing 196 trials in total. Prior to the experimental session, the participants were given 32 practice trials, so that they could see the variety of movements twice and adjust their own relative scale.

6.2 *Results*

As for experiment 4, we only analysed participants' responses as a function of the kinematic variables of the artificial movements. Multiple regression analyses (stepwise regression analysis, with automatic exclusion of variables by the default procedure of the SPSS software) were performed on the perceptual weight judgments with the duration, acceleration, and amplitude of the lift as independent variables. This analysis revealed that 43.2% of the variance of the response was explained by the kinematics of the displayed movements: 34.8% was due to the acceleration during lift with a smaller contribution (8.4%) due to the amplitude of the lift. The lift duration was not involved in this analysis.

The individual analysis of the results showed large individual differences. Nine out of the twelve participants relied mainly on lift acceleration (between 40% and 94% of the variance explained) along with, in four of them, the amplitude of the lift, to explain a total of 78%–97% of the variance. Two participants relied mainly on the amplitude (explaining respectively 89% and 85% of the variance) with an added contribution of duration or acceleration to reach respectively 94% and 88% of the variance explained. The last participant showed intermediate results.

6.3 *Discussion*

The results of experiment 5 confirmed the results of experiment 4 that perceptual weight judgments are not directly linked to a variation of lift duration, but rather they rely on variations of acceleration. In both experiments 4 and 5, the variable was the mean acceleration during lift, but this does not exclude the possibility that observers could be sensitive to the initial acceleration. The importance of the acceleration suggests a faster perception of the weight grasped by another person than in the case of an observer sensitive to the duration of lift (which would imply delays greater than 200 ms; see figure 6b). This is probably important for joint actions. Meulenbroek et al (2007) showed that people lifting an object of varying weight placed on a table by another person are less surprised by the weight than the person that placed the object. The timing of perceptual weight judgments could be particularly important when one has to prepare oneself to receive a load directly transmitted by another person, which occurs frequently in daily life. In addition, it has been shown that, in an interception task, purely visual information on object movement is biased by the anticipation of the effects of gravity according to the context (see Senot et al 2005; Zago et al 2008).

7 General discussion

In the study reported here we investigated, in the context of perceptual weight judgments, those parameters that are relevant for action observation and whether or not they match the ones that are relevant for action execution. In experiment 1, the participants were shown recordings of weights being lifted under two conditions of visualisation (working point and stick diagram); in experiment 2, we analysed the movements of twelve participants lifting different weights; in experiment 3, the participants were shown both their movements and another participant's movements, each of them with the two conditions of visualisation. Finally, in experiments 4 and 5, we presented artificially modified lifting movements in order to further investigate those parameters that are used during action observation.

The first main question investigated in these experiments relates to the amount and the type of information that observers use in order to recognise the weight of a lifted object. The results obtained from experiments 1 and 3 revealed that participants do not show better overall performance when viewing additional configural information consisting of the movements of the trunk, shoulder, arm, forearm, and hand joined by a stick diagram than when viewing the working-point displacement only. However, as will be detailed below, the type of information that observers used differed as a function of the conditions. Given that in the two conditions of visualisation the participants' responses increased consistently with increasing weight, this result might be taken to suggest that the kinematics of the working point is sufficient to infer the kinetic property of weight. This result is consistent with previous studies (eg Runeson and Frykholm 1981; Shim et al 2004) which revealed that observers can estimate accurately the weight of a lifted box directly from observing the lifting motion. In addition, our results demonstrate that a minimal display of the working point provides sufficient information about object weight. The observers were only sensitive to the kinematics of lifting and not to the other phases (reach, grasp, and place). Further analyses revealed that the specific variable used is the acceleration and not the duration of the lifting movement. This was verified in most of the experimental conditions (three conditions of experiments 3, 4, and 5) and in most of the participants (experiments 4 and 5). Our results thus demonstrate that observers are specifically sensitive to the upward acceleration of the object during lift and not to the duration of the lift. As discussed above, the use of acceleration instead of duration to predict the weight of objects manipulated by another person might be particularly relevant in the context of joint actions (eg Meulenbroek et al 2007).

The second main question investigated in this study relates to the effect of ownership, which can be divided into two subquestions: did the participants manage to recognise their own movements? And did they have better performance when viewing their own movements? With respect to the recognition of one's own movements, contradictory results appear in the literature. For instance, two studies investigated self-recognition using Johansson's (1973) point-light technique. One of the studies did not find evidence of successful self-recognition (Cutting and Kozlowski 1977) whereas the other found a small advantage for recognising one's own gait (Beardsworth and Buckner 1981). With respect to the latter study, it has been hypothesised that self-recognition can be explained by the assumption that, when watching the point-light display, observers can derive anatomical structure from the multiple moving objects (Knoblich and Flach 2003). Other studies have found evidence of successful self-recognition. For instance, the participants in a study by Knoblich and Prinz (2001) were requested to identify handwriting from the kinematics alone, and they were able to distinguish self-produced trajectories from those produced by others, even one week after their production. Repp (1987) found that the participants in his study were able to recognise their own clapping. Interestingly, the participants in Prasad and Shiffrar's (2009) study were not able to identify their own actions from egocentric views (represented by point-light displays) but they were able to do so from allocentric views (both from front and rear views). Given that people have experience of seeing their own actions from first-person views and have little experience seeing themselves from behind or from third-person views, the authors concluded that their findings suggest that visual learning cannot account for enhanced visual sensitivity to self-generated action. With respect to the relative performance levels when viewing one's own movements versus others' movements many studies reported better results in the former case. For instance, people are more accurate when viewing their own movements for predicting the future course of handwriting trajectories (Knoblich et al 2002) and for predicting the landing position of a dart (Knoblich and Flach 2001).

In the study reported here, the participants were not able to recognise which session corresponded to their own movements above chance level. In addition, when considering the participants' raw results, there was no difference in weight-judgment performance when the participants viewed their own movements and when they viewed someone else's movements. However, interesting differences emerged when considering the kinematic parameters on which the participants relied in order to perform the task. Two main hypotheses can be put forward in order to explain the lack of differences found in the performance of experiment 3 between self and other conditions. First, it has been suggested that observers can mix up their own actions with similar actions produced by others, especially when those actions are depicted from non-egocentric perspectives (eg Fourneret and Jeannerod 1998; see also Loula et al 2005) and, indeed, in our experiments the graphical animations were shown from a side view and not from an egocentric axial perspective.

Alternatively, the differences seen as a function of the conditions might be taken to suggest limitations in the attentional processes required to perform the task. The participants might have implicitly extracted different types of information as a function of the different conditions while being unable to use all the parameters shown in the display, which would have improved their performance. Consistent with this hypothesis, the participants used several kinematic cues which differed from one condition to another. The kinematic cues used involved the mean acceleration, maximal height, duration of grasp, and even included cues that are irrelevant for perceptual weight judgments (such as reach duration). It should be stressed again here that such differences indicate that the participants are able to process various kinematic parameters and therefore the lack of differences in overall performance cannot be attributable to the setup that was used. In addition, in the conditions with the stick-diagram display, participants' global performance was not improved as compared to the conditions with the working-point display (as suggested by the lesser amount of variance explained by the kinematic variables). Rather, performance seemed to rely on parameters that were not quantified here and that were probably linked to the posture of the person represented in the stick diagram. The hypothesis of the role of posture on the stick-diagram display would be consistent with the fact that people's posture seen on photographs can be used to perform perceptual weight judgments (Valenti and Costall 1997).

The third main question investigated in this study concerned the differences in the parameters relevant for action execution and for action observation. The multiple regression analyses conducted on the results of experiment 2 revealed that during action execution five kinematic parameters varied consistently with weight: the mean acceleration, the maximal height, the durations of grasp, acceleration, and deceleration. These parameters thus could provide the observers with information on weight. During action observation, although the parameters used to perform the perceptual weight judgment task differed as a function of the four experimental conditions, they did not match those of action execution and never included all of them. As discussed above, the observers were selectively sensitive to acceleration which explained the largest part of the variance of the responses (except in the stick-diagram—other condition of experiment 3). By contrast, the acceleration explained a relatively small part of the variance of the information related to weight during action execution. The other important variable for action recognition is the maximal height during lift (particularly in the stick-diagram—other condition of experiment 3). This was confirmed in experiment 5 in which two participants out of twelve chose to rely mainly on maximal height. By contrast, maximal height was poorly related to weight, since only the lightest weight was lifted higher than the others (experiment 2). Experimentally, an overshoot of the lifted object is observed when the weight is suddenly lighter than anticipated after a blocked series of lifts with a constant weight (Johansson and Westling 1988). It might be the case that the observers in our study behaved as if the experiments were performed according to this protocol whereas, in contrast, the height of the lift is rather stable in random or ordinary conditions.

In summary, three main theories tried to give an account of observers' sensitivity to human movements. The visual hypothesis proposes that movement recognition can be performed through a purely visual analysis. The strong motor-simulation hypothesis suggests a simulation of the observed actions by the motor system leading to a resonance between the actor and the observer thanks to brain regions with mirror properties (Gallese et al 2004; Rizzolatti et al 2001). The weaker version of the motor-simulation hypothesis suggests a motor representation of the goals of the observed action without involving the encoding of all the kinematic details of the action. This latter proposal is supported by the observation that mirror neurons code the goal of the action but not the kinematic details of movements (Fogassi et al 2005). The present study reveals that the cues used for action observation are (i) sensitive to the type of display despite similar overall performance, and (ii) qualitatively and quantitatively different from the variables that actually vary with weight during action execution. These differences provide arguments against the strong version of the motor-simulation hypothesis. We suggest, instead, that observers choose visual cues with high diagnostic value (such as acceleration) or rely on de-contextualised assumptions, but do not use an exact copy of action execution. In addition, a purely visual analysis could not explain that different cues were used when the participants observed their own movements and someone else's movements. Taken together, our results are thus consistent with the weaker version of the motor-simulation hypothesis. It should be mentioned that results on perceptual weight judgments (an elementary cognitive act) cannot be directly used to understand more complex actions and intentions. However, our findings suggest that even at that elementary level, action recognition cannot be fully explained by simulation. As such, they add to the body of evidence discussed in depth by Jacob (2009) arguing that 'mind-reading' cannot be simply explained by resonance or 'tuning fork' mechanisms.

Acknowledgments. This research was supported by a grant from the European Communities: NEST project Hand-to-Mouth contract no 029065. Agnes Roby-Brami is supported by INSERM.

References

Atkeson C G, Hollerbach J M, 1985 "Kinematic features of unrestrained vertical arm movements" *Journal of Neuroscience* **5** 2318 – 2330

Barclay C, Cutting J, Kozlowski L, 1978 "Temporal and spatial factors in gait perception that influence gender recognition" *Perception & Psychophysics* **23** 145 – 152

Beardsworth T, Buckner T, 1981 "The ability to recognize oneself from a video recording of one's movements without seeing one's body" *Bulletin of the Psychonomic Society* **18** 19 – 22

Bingham G P, 1987 "Kinematic form and scaling: Further investigations on the visual perception of lifted weight" *Journal of Experimental Psychology: Human Perception and Performance* **13** 155 – 177

Bingham G P, 1993 "Scaling judgments of lifted weight: lifter size and the role of the standard" *Ecological Psychology* **5** 31 – 64

Blakemore S J, Decety J, 2001 "From the perception of action to the understanding of intention" *Nature Reviews Neuroscience* **2** 561 – 567

Brouwer A M, Georgiou I, Glover S, Castiello U, 2006 "Adjusting reach to lift movements to sudden visible changes in target's weight" *Experimental Brain Research* **173** 629 – 636

Brownlow S, Dixon A R, Egbert C A, Radcliffe R D, 1997 "Perception of movement and dancer characteristics from point-light displays of dance" *Psychological Record* **47** 411 – 421

Bülthoff I, Bülthoff H H, Sinha P, 1998 "Top – down influences on stereoscopic depth perception" *Nature Neuroscience* **1** 254 – 257

Cutting J E, 1978 "Generation of synthetic male and female walkers through manipulation of a biomechanical invariant" *Perception* **7** 393 – 405

Cutting J E, Kozlowski L T, 1977 "Recognizing friends by their walk: Gait perception without familiarity cues" *Bulletin of the Psychonomic Society* **9** 353 – 356

Decety J, Grèzes J, 1999 "Neural mechanisms subserving the perception of human actions" *Trends in Cognitive Sciences* **3** 172 – 178

Dittrich W H, Troscianko T, Lea S E G, Morgan D, 1996 "Perception of emotion from dynamic point-light displays represented in dance" *Perception* **25** 727 – 738

Dokic J, Proust J, 2002 *Simulation and Knowledge of Action* (Amsterdam: John Benjamins)

Eastough D, Edwards M G, 2007 "Movement kinematics in prehension are affected by grasping objects of different mass" *Experimental Brain Research* **176** 193 – 198

Fogassi L, Ferrari P F, Gesierich B, Rozzi S, Chersi F, Rizzolatti G, 2005 "Parietal lobe: from action organization to intention understanding" *Science* **308** 662 – 667

Fourneret P, Jeannerod M, 1998 "Limited conscious monitoring of motor performance in normal subjects" *Neuropsychologia* **36** 1133 – 1140

Gallese V, Fadiga L, Fogassi L, Rizzolatti G, 1996 "Action recognition in the premotor cortex" *Brain* **119** 593 – 609

Gallese V, Goldman A, 1998 "Mirror neurons and the simulation theory of mind-reading" *Trends in Cognitive Sciences* **2** 493 – 501

Gallese V, Keysers C, Rizzolatti G, 2004 "A unifying view of the basis of social cognition" *Trends in Cognitive Sciences* **8** 396 – 403

Gentilucci M, 2002 "Object motor representation and reaching – grasping control" *Neuropsychologia* **40** 1139 – 1153

Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Boston, MA: Houghton Mifflin)

Giese M A, Poggio T, 2003 "Neural mechanisms for the recognition of biological movements" *National Review of Neurosciences* **4** 179 – 192

Gordon A M, Forssberg H, Johansson R S, Westling G, 1991 "Visual size cues in the programming of manipulative forces during precision grip" *Experimental Brain Research* **83** 477 – 482

Grèzes J, Frith C D, Passingham R E, 2004 "Inferring false beliefs from the actions of oneself and others: An fMRI study" *NeuroImage* **21** 744 – 750

Hamilton A F, Joyce D J, Flanagan J R, Frith C D, Wolpert D M, 2007 "Kinematic cues in perceptual weight judgement and their origins in box lifting" *Psychological Research* **71** 13 – 21

Hanneton S, Dedobbeler S, Hoellinger T, Roby-Brami A, 2011 "Kinemagnetography for the direct kinematic modeling of the upper limb during trunkassisted reaching" *Journal of Applied Biomechanics* **27** 272 – 277

Hommel B, Musseler J, Aschersleben G, Prinz W, 2001 "The theory of event coding (TEC): a framework for perception and action planning" *Behavioral and Brain Sciences* **24** 849 – 878

Jacob P, 2009 "The tuning-fork model of human social cognition: A critique" *Consciousness and Cognition* **18** 229 – 243

Jacobs A, Pinto J, Shiffrar M, 2004 "Experience, context, and the visual perception of human movement" *Journal of Experimental Psychology: Human Perception and Performance* **30** 822 – 835

James W, 1890 *The Principles of Psychology* (New York: Holt)

Johansson G, 1973 "Visual perception of biological motion and a model of its analysis" *Perception & Psychophysics* **14** 201 – 211

Johansson R S, Westling G, 1984 "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects" *Experimental Brain Research* **56** 550 – 564

Johansson R S, Westling G, 1988 "Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip" *Experimental Brain Research* **71** 59 – 71

Knoblich G, Flach R, 2001 "Predicting effects of actions: Interactions of perception and action" *Psychological Science* **12** 467 – 471

Knoblich G, Flach R, 2003 "Action identity: Evidence from self-recognition, prediction, and coordination" *Consciousness & Cognition* **12** 620 – 632

Knoblich G, Prinz W, 2001 "Recognition of self-generated actions from kinematic displays of drawing" *Journal of Experimental Psychology: Human Perception and Performance* **27** 456 – 465

Knoblich G, Seigerschmidt E, Flach R, Prinz W, 2002 "Authorship effects in the prediction of handwriting strokes: Evidence for action simulation during action perception" *Quarterly Journal of Experimental Psychology* **55** 1027 – 1046

Kozlowski L, Cutting J, 1977 "Recognizing the sex of a walker from a dynamic point-light display" *Perception & Psychophysics* **21** 575 – 580

Loula F, Prasad S, Harber K, Shiffrar M, 2005 "Recognizing people from their movements" *Journal of Experimental Psychology: Human Perception and Performance* **31** 210 – 220

Meulenbroek R G, Bosga J, Hulstijn M, Miedl S, 2007 "Joint-action coordination in transferring objects" *Experimental Brain Research* **180** 333 – 343

Pollick F E, Kay J W, Heim K, Stringer R, 2005 "Gender recognition from point-light walkers" *Journal of Experimental Psychology: Human Perception and Performance* **31** 1247 – 1265

Prasad S, Shiffrar M, 2009 "Viewpoint and the recognition of people from their movements" *Journal of Experimental Psychology: Human Perception and Performance* **35** 39 – 49

Prinz W, 1997 "Perception and action planning" *European Journal of Cognitive Psychology* **9** 129 – 154

Repp B H, 1987 "The sound of two hands clapping: An exploratory study" *Journal of the Acoustical Society of America* **81** 1100 – 1109

Rizzolatti G, Craighero L, 2004 "The mirror – neuron system" *Annual Review of Neuroscience* **27** 169 – 192

Rizzolatti G, Fogassi L, Gallese V, 2001 "Neurophysiological mechanisms underlying imitation and the understanding of action" *Nature Reviews Neuroscience* **2** 661 – 670

Runeson S, Frykholm G, 1981 "Visual perception of lifted weight" *Journal of Experimental Psychology: Human Perception and Performance* **7** 733 – 740

Runeson S, Frykholm G, 1983 "Kinematic specification of dynamics as an informational basis for person-and-action perception: expectation, gender recognition, and deceptive intention" *Journal of Experimental Psychology, General* **112** 585 – 615

Scholtz J P, Millford J P, McMillan A G, 1995 "Neuromuscular coordination of squat lifting, I: Effect of load magnitude" *Physical Therapy* **75** 119 – 132

Scully D M, Newell K M, 1985 "Observational learning and the acquisition of motor skills: Toward a visual perception perspective" *Journal of Human Movement Studies* **11** 169 – 186

Senot P, Zago M, Lacquaniti F, McIntyre J, 2005 "Anticipating the effects of gravity when intercepting moving objects: differentiating up and down based on non-visual cues" *Journal of Neurophysiology* **94** 4471 – 4480

Shim J, Carlton L G, 1997 "Perception of kinematic characteristics in the motion of lifted weight" *Journal of Motor Behavior* **29** 131 – 146

Shim J, Carlton L G, Kim J, 2004 "Estimation of lifted weight and produced effort through perception of point-light display" *Perception* **33** 277 – 291

Stevens J A, Fonlupt P, Shiffrar M, Decety J, 2000 "New aspects of motion perception: Selective neural encoding of apparent human movements" *NeuroReport* **11** 109 – 115

Stoffregen T A, Flynn S B, 1993 "Visual perception of support-surface deformability from human body kinematics" *Ecological Psychology* **6** 33 – 64

Valenti S, Costall A P, 1997 "Visual perception of lifted weight from kinematic and static (photographic) displays" *Journal of Experimental Psychology: Human Perception and Performance* **23** 181 – 198

Viviani P, Stucchi N, 1992 "Biological movements look constant: Evidence of motor – perceptual interactions" *Journal of Experimental Psychology: Human Perception and Performance* **18** 603 – 623

Weir P L, MacKenzie C L, Marteniuk R G, Cargoe S L, Frazer M B, 1991 "The effects of object weight on the kinematics of prehension" *Journal of Motor Behavior* **23** 192 – 204

Wilson M, 2001 "Perceiving imitatible stimuli: Consequences of isomorphism between input and output" *Psychological Bulletin* **127** 543 – 553

Zago M, McIntyre J, Senot P, Lacquaniti F, 2008 "Internal models and prediction of visual gravitational motion" *Vision Research* **48** 1532 – 1538

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 40 2011

www.perceptionweb.com