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Weight perception during action observation: the role of motor skills and abilities

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Outline of the thesis

The aim of this work is to investigate the role that motor skills and abilities have in perceiving the weight of an object handled and moved by another person. This topic provides an understanding of the interaction between actions and perceptions by assessing how motor repertoire, either shaped during years of sport practice, or altered during aging and fatigability, modulates the way individuals perceived the movement performed by others.

The first chapter (*Chapter 1*) presents a summary of the scientific literature about this topic, and, in particular, of the mechanisms underlying it, primarily motor resonance. Next, the state of the art on the perception of the weight of an object during the execution and observation of a movement is presented.

The first study (*Chapter 2*) investigates the role of motor expertise and the acquisition of specific skills in assessing the weight of an object moved during a sport-specific gesture.

In the second study (*Chapter 3*), the role of ageing and the decline of motor ability in the ability to perceive the weight of an object during the observation of an everyday life movement was investigated.

In the third study (*Chapter 4*), the focus was on how the nature of the movement, i.e. concentric or eccentric movement, affected the ability to discriminate the weight of an object during action observation.

The fourth study (*Chapter 5*) focused on how the state of the observer could affect this ability, specifically how fatigue affects the ability to discriminate and evaluate the weight of an object during the observation of an everyday movement.

Chapter 1. Background

1.1. Motor resonance

Humans live in a word full of stimuli coming from other humans, animals, inanimate objects, sounds, and motions. How do people interpret these stimuli? How do they react to moving objects or actions performed by other humans? At the end of the 20th century, the discovery of the mirror neuron system (MNS) opened up a new field of research that provided the possibility of explaining the unexplored connection between perception of visual and auditory stimuli, movement, action understanding, and motor learning. All these processes seem to be connected to each other by a resonance mechanism that is evoked during action perception, namely *motor resonance*. Motor resonance is a phenomenon consisting of a significant increase of the activity of the brain's cortical areas during the observation of actions performed by other individuals and while listening to action sounds (G. Rizzolatti et al., 1999). The discovery of motor resonance gave rise to the *direct matching hypothesis*, which states that "we understand actions when we map the visual representation of the observed action onto our motor representation of the same action" (p. 661) (Giacomo Rizzolatti et al., 2001). This means that the motor knowledge of the observer "resonates" with the observed action and that "we understand an action because the motor representation of that action is activated in our brain" (p. 661) (Giacomo Rizzolatti et al., 2001). Due to its peculiar features, the activation of the MNS was also advanced as a prerequisite for imitation (Craighero et al., 2002; Iacoboni, 2009; Giacomo Rizzolatti et al., 2001), social/cognitive behaviors (Gallese & Goldman, 1998), and speech/language processing (Luciano Fadiga et al., 2002). In order to understand the principle of motor resonance and how it is involved in action understanding and motor imitation, it is useful to make a brief digression on the mirror neuron system and on its properties.

1.1.1. The mirror neuron system: the neurophysiological basis of motor resonance

Mirror neurons were described for the first time in 1992 as a class of cells in the monkey premotor area. This neurons class showed activation both when the animals performed an action and when they observed the action performed by performed by someone else (another monkey or an experimenter) (Giacomo Rizzolatti & Craighero, 2004). A few years after this discovery, these cells were called Mirror Neurons to emphasize the ability of motor areas to activate similarly when performing (or planning) and when observing an action (Bonini et al., 2022). Mirror neurons discovery started a very large strand of research in neuroscience, especially in human research, through non-invasive techniques. A huge amount of data from neurophysiological and brain imaging experiments provided strong clues on the existence of an MNS in humans also (Giacomo Rizzolatti & Craighero, 2004). The first evidence goes back to the studies on the reactivity of cerebral rhythms during movement observation performed by Gastaut and Bert (1954), who showed a modification of the electroencephalographic (EEG) mu rhythm typical of movement execution during movement observation (Gastaut & Bert, 1954). But it took 40 years for the terms mirror neuron and motor resonance to be associated with humans.

Initial evidence came from studies using transcranial magnetic stimulation (TMS). TMS is a non-invasive technique using a magnetic field to activate neurons located a few centimeters under the coil. A brief stimulation over the cortical representation of a body part in the primary motor cortex (M1) activates the corticospinal tract and evokes a response called motor evoked potential (MEP) in the corresponding contralateral muscle. By means of TMS, Fadiga and colleagues (1995) showed an increase of MEP amplitude when volunteers observed a grasping action or a meaningless arm gesture. This effect was only seen in the muscles that participants used for producing the observed movement. Motor facilitation was explained as the result of the increase activity of M1 due to the mirror activity of the premotor areas from which M1 receives input (L. Fadiga et al., 1995). This result was confirmed by Maeda and colleagues (2002), who found that this motor resonance effect was evoked during the observation of intransitive, not goal-oriented movement, differently from what was observed in monkeys (Maeda et al., 2002). Furthermore, another TMS study showed that the time course of cortical facilitation followed the phases of the observed action (Gangitano et al., 2001)Therefore, the results of TMS studies indirectly pointed out the existence of a human MNS, responsible for motor resonance mechanisms.

Brain imaging studies offered an overview of the areas that are part of mirror neuron system in humans, which include the supramarginal gyrus and adjacent intraparietal sulcus, the ventral premotor cortex, the posterior inferior frontal gyrus, the primary motor cortex, and supplementary motor area (Kemmerer, 2021; Giacomo Rizzolatti & Craighero, 2004).

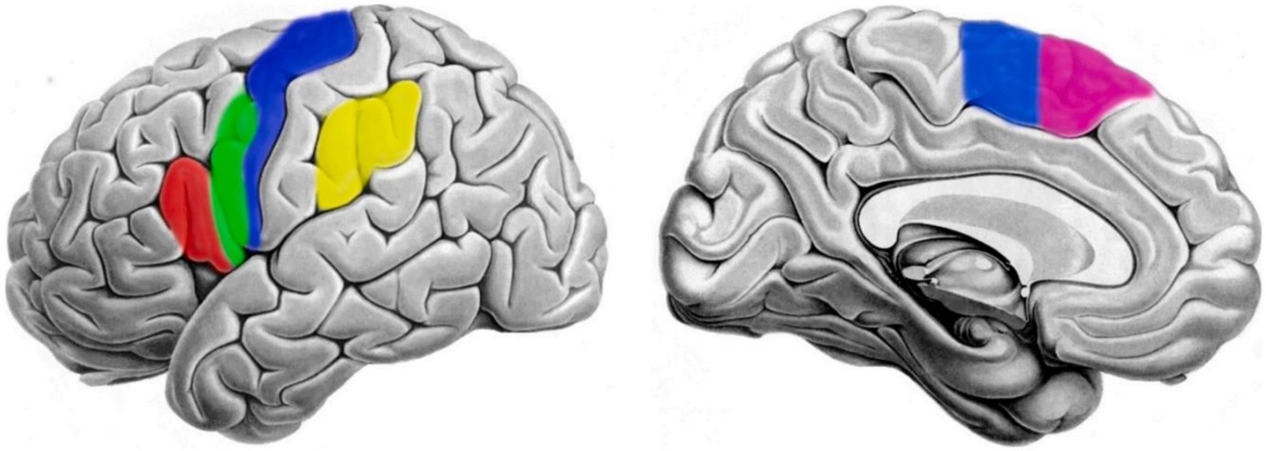

Figure 1. Parietal and frontal components of the human Mirror Neuron System (MNS). Areas: Supramarginal gyrus and adjacent intraparietal sulcus (yellow); the ventral premotor cortex (green); the posterior inferior frontal gyrus (red); the primary motor cortex (blue) and supplementary motor area (magenta) (Kemmerer, 2021).

The first direct proof of the existence of neurons with mirror properties in humans came from a study in 2010 (Mukamel et al., 2010). In this study, researchers realized single neuron recordings from epileptic patients implanted with intracranial depth electrodes and identified neurons with mirror properties in the supplementary motor cortex (SMA), hippocampus, and entorhinal cortex.

Mirror-neuron system has been seen to play a role in action understanding. Functional Magnetic Resonance Imaging (fMRI) experiments showed that the action intention was encoded; similar movements with different finalities lead to different activation in brain areas (Giacomo Rizzolatti & Craighero, 2004).

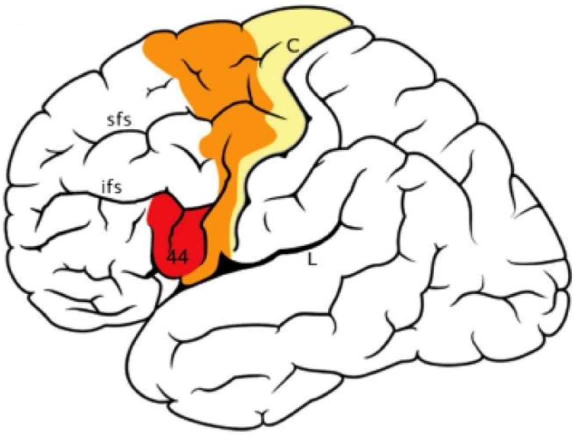

Figure 2. Broca's Area (In red); premotor cortex (in orange); primary motor cortex (in yellow); C: central sulcus; ias: inferior arcuate sulcus; ifs: inferior frontal sulcus; L: lateral sulcus; P: principal sulcus; sas: superior arcuate sulcus; sfs: superior frontal sulcus. From: Fogassi and Ferrari, 2016.

The Broca's area, located within IFG, is widely known as responsible for language production. More recent neurophysiological studies attributed a more important role to this area, not only in understanding language itself but more generally in understanding actions performed by others (Fazio et al., 2009; Fogassi & Ferrari, 2007). Indeed, Broca's area was associated with a complex pattern of abilities: language production, language perception, music and rhythms evaluation, syntactic violations, mathematical calculation, living eye contact and action perception (Luciano Fadiga et al., 2009). This area was especially activated during the observation of hand/mouth actions, it seemed to be able to assume a decisive role within the MNS, being involved into goal-directed actions (Fazio et al., 2009).

Therefore, once the existence of such neurons in humans has been demonstrated (although some controversies persist, see Hickok, 2009), it is important to present the experimental evidence that helps to understand how they are involved in action perception and movement planning.

1.1.2. Factors modulating motor resonance

The activity of MNS, and also motor resonance, has been shown to be modulated by several factors: factors involving the action; factors involving the actor; factors involving the observer; factors involving the relationship between actor and observer; and the factor of context (Kemmerer, 2021).

Factors involving the action. Transitive actions (directed toward objects in peripersonal space) involved a higher activation of the MNS than intransitive movement (Caspers et al., 2010). The kinematic features of the observed action modulate motor resonance. In a study by Saygin and colleagues (2004), participants' brain activity was monitored by means of functional magnetic resonance imaging (fMRI) technique during the observation of point-light biological motion (Johansson, 1973) and scrambled animations. The results showed that actions characterized by solely motor cues activate the frontal part of the MNS. In particular, frontal areas showed selective increased responsivity to biological motion compared with scrambled stimuli, supporting the hypothesis that motion information can drive inferior frontal and premotor areas involved in action perception (Saygin et al., 2004). The importance of recognizing the biological origin in the observed movement was shown also in studies on automatic imitation, namely the automatic tendency to mimic the features of the observed movement, which is considered as a sign of the activation of motor resonance mechanisms. It was shown that when the visual display violated the biological law of motion, automatic imitation did not occurred (Bisio et al., 2010, 2012, 2014).

Static actions were recognized only if within a recognized motor pattern and/or with a recognized goal but, intuitively, dynamic actions involved a more effective pattern of activation (Ferri et al., 2015). Rather interesting, especially in deciding the experimental setting, is how real the observed action is perceived to be; live stimuli evoked higher corticospinal excitability (in a TMS study) than recorded (Prinsen & Alaerts, 2019), and 3D actions evoked greater responses than 2D, although they still turned out to be environmentally unfriendly and not always pleasant by participants (Ferri et al., 2016).

Factors involving the actor. Several studies have investigated the role of the nature of the actor on triggering the motor resonance of the observer, specifically an artificial agent such as a robot, but the results were uncertain. For e.g., in a TMS study cortical excitability was increased similarly during observing a robot and human actions (Hogeveen & Obhi, 2012). Otherwise, a fMRI showed that in both parietal and premotor regions the response was higher with a robot than a human nevertheless participants reported that robot moved with less naturalness and the goal of action was less clear (Kupferberg et al., 2018). However, it seems to be the action and context, rather than the nature of the actor, that activates the motor resonance (Hogeveen & Obhi, 2012).

Factors involving the observer. Factors concerning observer influenced MNS more than others. Awareness, expectation of the action to be observed, as well as the level of attention, result in greater activation of the MNS and greater action perception.

Despite the research focused more on right-handers than left-handers, evidence showed a role for manual dexterity in modulating the MNS, hand preference strongly influenced motor resonance. One of the most investigated factors is the modulation of action familiarity and expertise. Familiarity with a movement led to better MNS engagement (Gardner et al., 2015). This familiarity also included the temporal characteristics of the observed movement (Avanzino et al., 2015). Social interaction, which could be considered an “experience”, increasing the attention, was shown to evoke motor resonance in human following actions. As demonstrated by several behavioral, neurophysiological and neuroimaging studies, emotions strongly modulated the MNS, especially the negative ones (Botta et al., 2021, 2022; Lagravinese et al., 2017; Schmidt et al., 2020). These intense responses could derived from an ancestral reaction to dangerous situations (Kemmerer, 2021) .

Factors involving the relationship between actor and observer. Postural congruence between actor and observer elicited a facilitation of the MNS activation (Alaerts et al., 2009). Observing an actor of own ethnicity led to a deeper engagement of the MNS, as well as the social group affiliation played a facilitating role (Liew et al., 2011). This group affiliation facilitation could be flexible according to the context. Motor resonance could be influenced by a prior eye contact, facilitating or hindering the MNS responses (Prinsen & Alaerts, 2019).

Context. Environment and social context modulated MNS, for instance corticospinal excitability increased if the action was direct to another person instead to an inanimate object or if the context was congruent or not (Bucchioni et al., 2013; Hogeveen & Obhi, 2012).

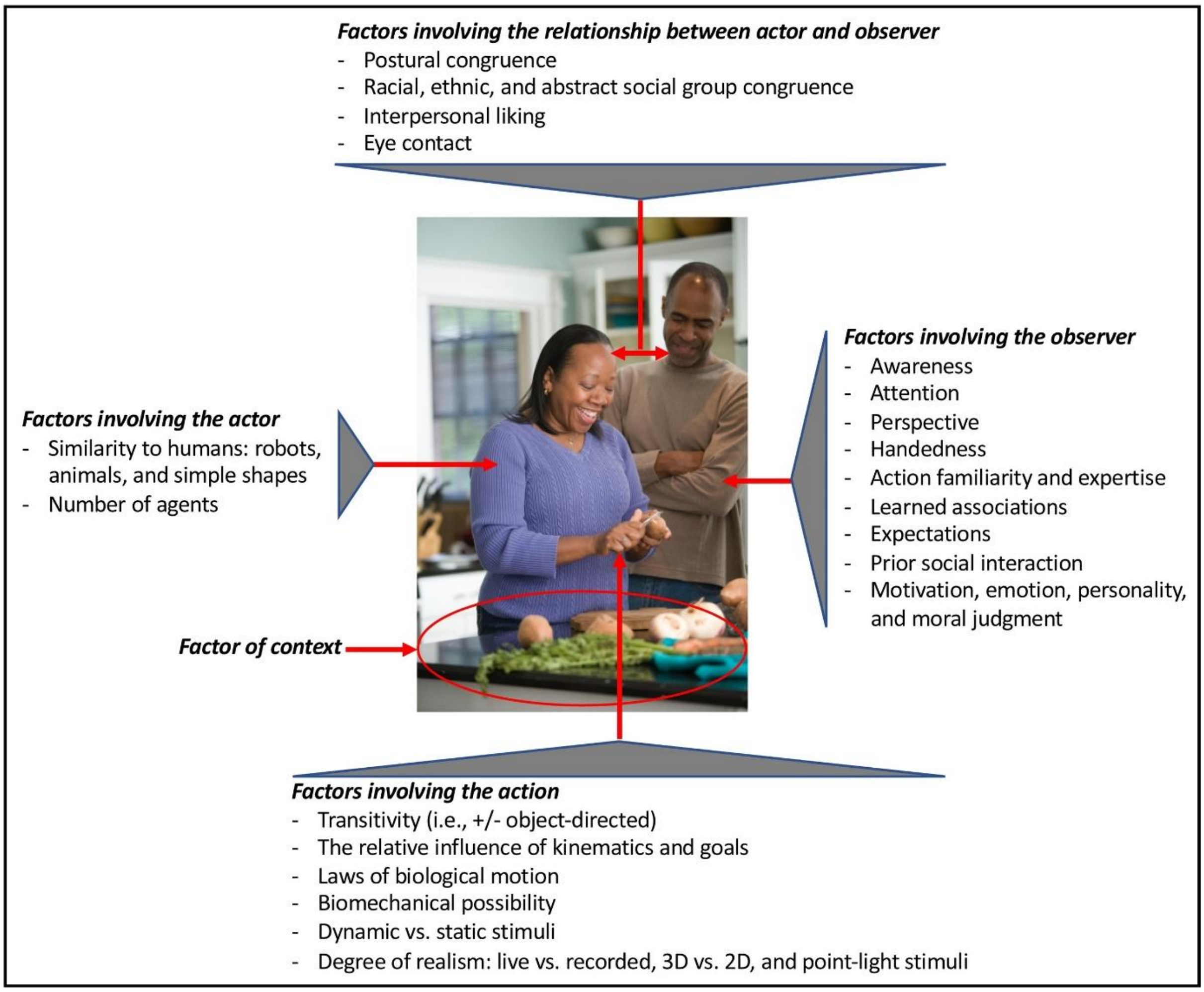

Figure 3. Factor Influencing MSN activity (Kemmerer, 2021).

1.1.3. The role of expertise in motor resonance

As above mentioned, action familiarity and expertise played a role in modulating motor resonance, meaning that the motor resonance is constrained to the acquired skills that person has learned. A particular action may figure in the motor repertoire of a trained expert but not in the motor repertoire of someone who has not been so trained. Calvo-Merino and colleagues (2005) used an fMRI paradigm to study groups of people with different acquired motor skills to investigate whether the brain's system for action observation is precisely tuned to the individual's acquired motor knowledge (Calvo-Merino et al., 2005). Expert ballet and capoeira dancers watched videos of ballet and capoeira movements. Thus, both groups saw identical stimuli, but only had motor experience of the actions in their own dance style. Comparing the brain's activity when dancers watched their own dance style versus the other style revealed the influence of motor expertise on action observation, namely, an increased bilateral activation in the MNS regions when expert dancers viewed movements that they had been trained to perform compared to movements they had not. This result was attributable to the motor and not the visual familiarity, as suggested by the results of a following study by the same group of researchers, in which male and female dancers watched gender and non-gender-specific videos (Calvo-Merino et al., 2006). Indeed, the visual familiarity was the same, but some ballets were performed by only one gender. Authors found greater premotor, parietal, and cerebellar activity when dancers viewed moves from their own motor repertoire, compared to opposite-gender movements that they frequently saw but did not perform, confirming the role of the motor rather than the visual knowledge in activating motor resonance mechanisms. These findings were subsequently confirmed by several fMRI studies that tackled the role of motor expertise during different kinds of tasks involving the observation of sport-related actions (Abreu et al., 2012; Balser, Lorey, Pilgramm, Naumann, et al., 2014; Balser, Lorey, Pilgramm, Stark, et al., 2014; Bishop et al., 2013; Wright et al., 2010).

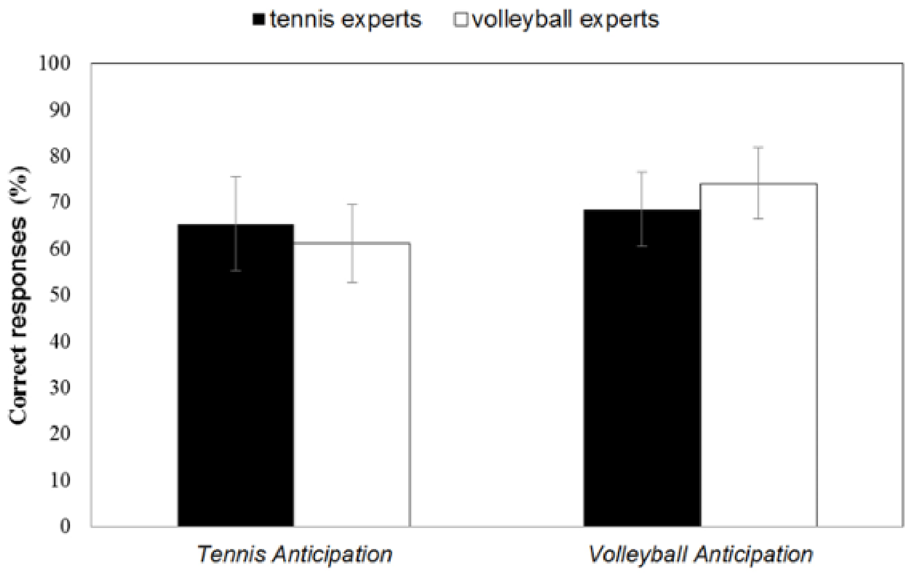

Figure 4. Mean percentage of correct responses in the Tennis Anticipation and the Volleyball Anticipation condition of the tennis experts and the volleyball experts. Bars represent SD (from Balser, Lorey, Pilgramm, Naumann, et al., 2014)

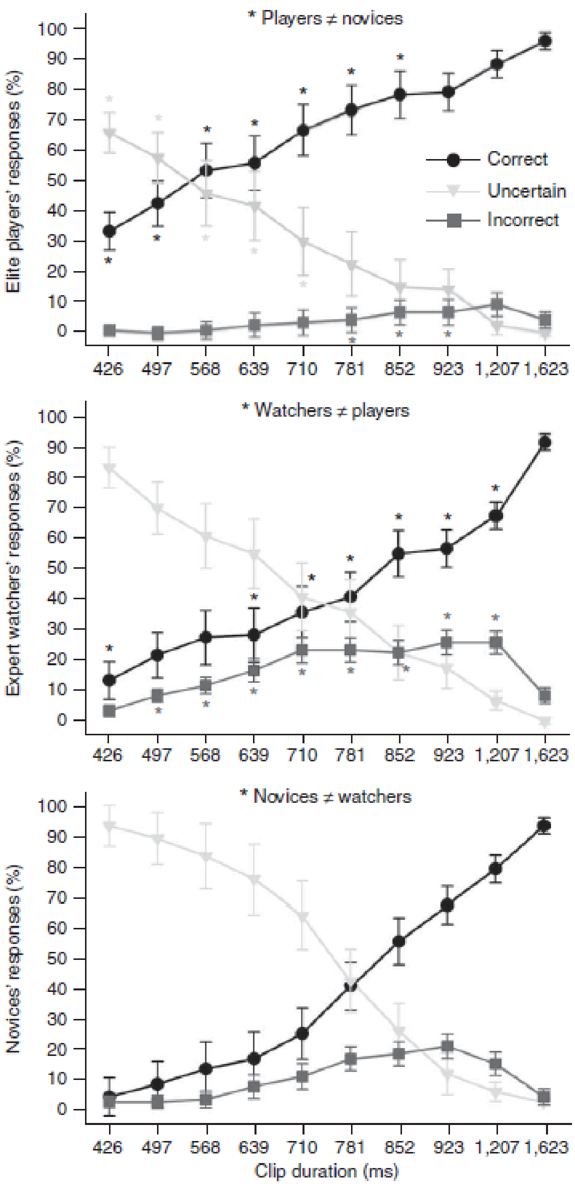

Figure 5. Percentages of uncertain, correct and incorrect responses (mean ± s.e.m.) made by the elite player, expert watcher and novice groups at the different clip durations (Figure 1, from Aglioti et al., 2008).

Another body of evidence in support of this hypothesis comes from behavioral and neurophysiological research by Aglioti and colleagues (2008) on action anticipation in basketball players. In a first psychophysical experiment using a temporal occlusion paradigm, authors asked the subjects (elite basketball players, expert watchers, and novices) to predict the outcome of basketball shots observed in a movie. The results showed that basketball players predicted the outcome of free shots earlier and more accurately than people who have similar visual expertise but no direct motor experience with basketball, namely expert watchers and novices. In a neurophysiological experiment of the same study, they also showed an increase of motor excitability in athletes and expert watchers when they observed a basket action (shots in or out of the basket), rather than a soccer action or a static image. However, a specific increase of motor facilitation for the hand muscle more directly involved in controlling the ball trajectory, and for the instant at which the ball left the hand was only found when basketball players observed out shots. The results indicate that "although mere visual expertise may trigger motor activation during the observation of domain-specific actions, a fine-tuned motor resonance system subtending elite performance develops only as a consequence of extensive motor practice" (p. 1114) (Aglioti et al., 2008).

1.2. Perception of weight

Before picking up an object, individuals implicitly estimate its weight, based on visual properties and expectation. When involved in a cooperative task, people estimate object’s weight from other movement.

1.2.1. Weight perception during action execution

The study of weight perception began with Ernst Weber, the pioneer of the psychophysics (Jones, 1986). Weber (1834) was the first to study weight perception and its relation to sensitivity and the *muscular sense*. The evaluation of weight is quite accurate with the touch of it and with more subsequent manipulation (Jones, 1986). Weber's experiments were taken up later by Ferrier (1886) and Waller (1891) and others who evaluated weight discrimination ability under different conditions of muscle activation. From this time, scholars began to question the nature of the origin of such sensation. The first hypothesis attributed the origin of force and heaviness sensations to peripheral afferences but, as early as the late nineteenth century, a theory of a central origin was proposed, where the sensations arise centrally after receiving stimuli from the periphery of our body (Jones, 1986).

Factors such as strength capacity or training influence load discrimination. Weight perception was explored in contexts of gravity alteration (micro- and macro-gravity). The findings showed a decrease in weight discrimination ability, only partially restored after permanence in altered gravity environments. The authors hypothesized that humans are not as sensitive to inertial mass as they are to weight (Jones, 1986). Practice in object’s lifting influences the ability to produce the correct grip strength and load force, as suggested by Buckingham and colleagues (Buckingham et al., 2018), who showed that during the first time object is moved several errors in the grip strength and load force occurred. These errors quickly disappeared through practice as consequence of changes in expectation (Buckingham et al., 2018).

The sense of heaviness relates to the weight of objects, and peripheral afferences play a key role in its determination. This sense is experienced when moving objects or when two objects placed on hands are compared (Proske & Allen, 2019). Former studies in the seventies showed that moving objects facilitated heaviness discrimination, suggesting that the peripheral contribution provides useful information (McCloskey et al., 1974). Proske & Gandevia published a review in 2012, placing a milestone in the understanding and knowledge of proprioceptive sense. They definitely pointed out the role of motor command and peripheral inputs (muscle spindle plays a key-role) in the sense of heaviness (Proske & Gandevia, 2012).

Intuitively, heaviness sense could be influenced by the size of the object involved. Usually, larger objects contained more material and people estimated them heavier than smaller ones. The size-weight illusion is the phenomenon that the smaller of two equally heavy objects is perceived to be heavier than the larger object when lifted (Plaisier & Smeets, 2015). The authors observed that the heaviness perception was influenced more by size than by knowledge of the content of the object (Plaisier & Smeets, 2015). This phenomenon occurred due to a mismatch between a sensorimotor prediction and sensory feedback, namely an incongruence between expectation and experience (Kambara et al., 2013). The size-weight illusion was modulated by training, meaning that experience reduces illusion (Flanagan & Bandomir, 2000).

1.2.2. Weight perception during others' action

Perceptual weight judgment studies were used to understand the link between motor performance and action observation (Auvray et al., 2011). These study included various procedures, static pictures (Valenti & Costall, 1997), point-light displays and videos (A. Hamilton et al., 2007).

Individuals implicitly learn the weight of an object using kinematic information obtained when others lifted the object (Meulenbroek et al., 2007). Weight perception arises from both physical appearance and sensitivity to human movement. Even at reduced kinematic information (e.g., point-light technique) several experiments showed a preserved ability to evaluate the weights lifted of lifted objects (Johansson, 1973; Shim & Carlton, 1997).

Two main hypotheses have been put forward to explain how people assessed the features of the objects involved in the actions of others. The first one was based on the role human abilities have as facilitator in motion perception. The sensitivity arose from both visual and motor system (Viviani & Stucchi, 1992). During the process of understanding others' movement, the perception is accompanied by an action simulation and these components are strictly connected and influenced each other

(Auvray et al., 2011). As result, the motor repertoire, which influences the motor response, determines also individuals' perception (White, 2012). The second hypothesis attributes our understanding of others' action only to visual analysis (Johansson, 1973). This "only visual theory" refuses the need of action simulation. Visual sensitivity derived from observer visual expertise; this hypothesis was supported by many point-light experiment in which observing from unusual perspective the same movements lead to a decrease in performance (Tarr & Bülthoff, 1998).

Two studies by Alaerts and colleagues helped to clarify this point. By assessing the excitability of the primary motor cortex trough TMS, they showed that the mere observation of videos showing an actor lifting objects leaded to activation of motor areas (in line with the motor resonance theory), and the heavier the weight, the greater the motor potential evoked (Alaerts et al., 2009; Alaerts, Swinnen, et al., 2010). These findings supported the main role of motor system in heaviness perception. In fact, action observation of lifting led not only to action-specific muscle activation in the observer, but also modulated M1 excitability on the basis of the changes of the force expressed in the observed action. Thus, observation-to-execution mapping included also some dynamical features of motor control, such as grip force (Alaerts, Senot, et al., 2010).

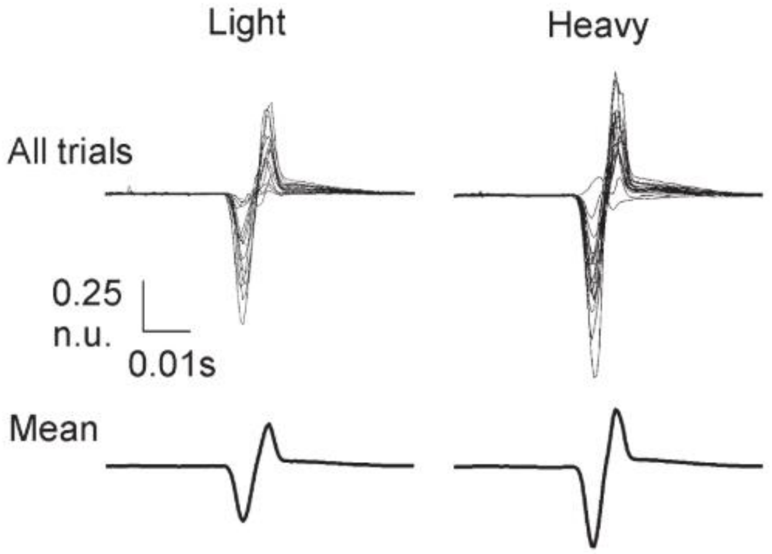

Figure 6. A representative example of individual MEPs recorded from the FDI muscle during observation of lifting a light and heavy object. From Alaerts, Swinnen, et al., 2010

Several studies investigated which properties of the observed action determined the judgment of the weight during objects' manipulation. Runeson and Frykholm reported the importance of kinematics information during moving-objects perception and proposed the expectation and the intrinsic recognition of intention as key factors (Runeson & Frykholm, 1981). Furthermore, actor posture and inter joint coordination were shown to be sources of information for the observers during action observation task requiring weight evaluation (Valenti & Costall, 1997).

More recent studies put the focus on the role that movement kinematics has in perceptual weight discrimination. Hamilton et colleagues investigated which phases of the movement became more relevant during the judgement (Figure 7) (A. Hamilton et al., 2007). Results showed that the lifting phase were influenced by the weight, and that changing in speed and acceleration became determinant for the observer during weight perception (Auvray et al., 2011).

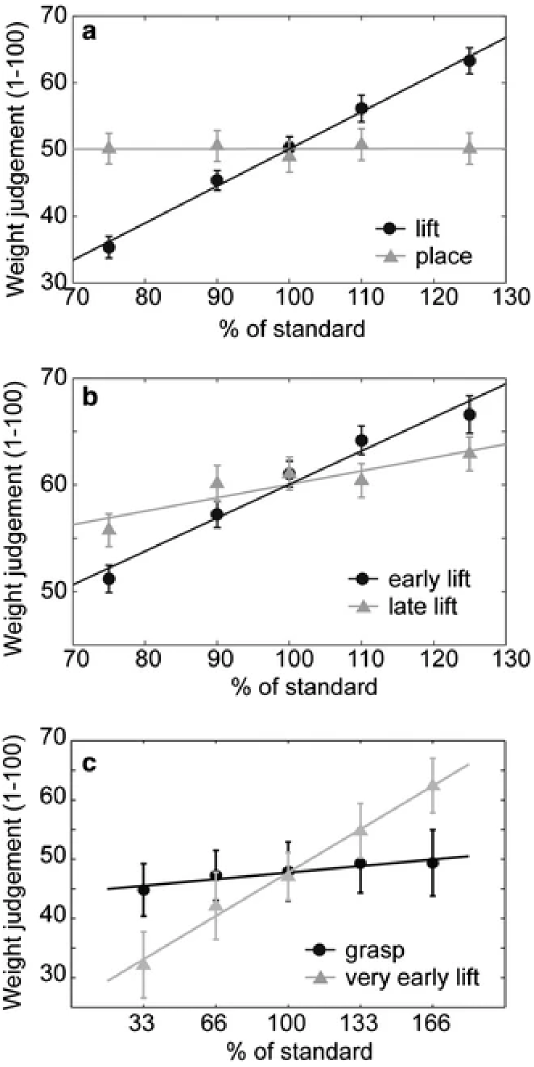

Figure 7. Results of experiments 3, 4 and 5. Mean weight judgement across participants with standard error bars are shown as points, and best fit regression lines are shown in the *same colour*. (A) Experiment 3 revealed that lift duration has a reliable linear effect on weight judgement (*dark line*) and place duration has no effect (*pale line*). (B) Experiment 4 revealed that both early and late lift durations influence weight judgement, but that the effect of early lift is stronger. (C) Experiment 5 revealed that very early lift influences weight judgement but grasp duration does not.

The nature of actor did not influence weight judgment ability; indeed no differences were found observing oneself or others (Auvray et al., 2011). In addition, sensations arising from our body contribute to interpreting the actions of others (Hamilton et al., 2004). For e.g., Hamilton et al. (2004) observed that weight judgment changed when the observer manipulated a box themselves. Participants judged the box moved by the actor to be heavier when they were physically lifting a light box, and vice versa. In a following study, the authors noted the activation of both motor and visual areas, suggesting the main role but not exclusively of the motor system (A. Hamilton et al., 2007)

Not only the actor's movement kinematics and object characteristics helped in weight evaluation during an action observation. The effort of the actor and the force produced by the actor have been shown to be encoded while lifting objects was observed (Mizuguchi et al., 2016) and to modulate the activity of the motor areas of observer (Alaerts et al., 2010).

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Chapter 2. The role of the sensorimotor expertise in weight perception during an action observation task

This study aimed to investigate the role of sensorimotor expertise in evaluating the weight of a lifted object during the observation of a sport-specific gesture, namely the deadlift. Fifty-six participants, assigned to three groups according to their experience in weight lifting, powerlifters, CrossFit® practitioners and naïve participants (controls), performed a perceptual weight judgments task. Participants observed videos showing a powerlifter executing a deadlift at the 80%, 90% and 100% of 1 repetition maximum (1RM) and answered a question about the weight of the lifted object. Participants' response accuracy and variability were evaluated. Findings showed that powerlifters were more accurate than controls. No differences appeared between powerlifter and CrossFit® practitioners, and between CrossFit® practitioners and controls. Response variability was similar in the three groups. These findings suggest that a fine sensorimotor expertise specific for the observed gesture is crucial to detect the weight of the object displayed in the observed movement, since it might allow detecting small changes in the observed movement kinematics, which we speculate are at the basis of the object weight recognition.

2.1. Introduction

Scientific literature argues in favor of a common representation for the perception and the production of human movement. The seminal studies from Johansson put a milestone on the fact that humans are able to recognize biological entities based on few motion information during the observation of a point-light display (Grossberg, 2012; Johansson, 1973). Furthermore, studies using action observation paradigms showed that the perception of human motion can be improved by prior motor activity (Bidet-Ildei et al., 2010; Casile & Giese, 2006), and that this phenomenon is shaped by the perceptual motor similarities between self and other stimuli (Beardsworth & Buckner, 1981; Coste et al., 2021). These observations find a neurophysiological basis in the mirror neuron system, a network of frontal and parietal areas activated during both motor and perceptual tasks

(Giacomo Rizzolatti & Craighero, 2004; Schubotz & Von Cramon, 2001). The activation of this system was postulated to give rise to motor resonance, namely the activation of the observer's motor system during action observation (G. Rizzolatti et al., 1999). Indeed, motor resonance was shown to be influenced by the observer's motor experience (Giacomo Rizzolatti & Craighero, 2004), which models the individual motor repertoire, and to be prevented when the observer cannot recognize the biological origin of the observed movement (Bisio et al., 2010, 2014).

Another key issue to be considered is the role played by the individual's motor repertoire. For instance, the possibility to map the features of the observed action into the own motor repertoire increases motor resonance, as shown by action observation studies concerning both the temporal features of movements (Avanzino et al., 2015; Giovanna Lagravinese et al., 2017) and the ability to anticipate the outcome of an observed action (Bove et al., 2017; Martel et al., 2011; Pedullà et al., 2020). Studies comparing motor resonance in athletes and novices during the observation a sport gesture showed that motor resonance is greater when observing "known" than "unknown" movements (Aglioti et al., 2008; Calvo-Merino et al., 2005, 2006). Therefore, the possibility to match the observed movement kinematic into the own motor repertoire seems crucial to make prediction about the observed action.

It was also shown that the kinematics of the actor help the observer to infer the property of the object involved in the action, such as its weight (Auvray et al., 2011; A. Hamilton et al., 2007; Antonia Hamilton et al., 2004; Runeson & Frykholm, 1981; Shim et al., 2004), although it might be not sufficient, as suggested by Grierson and colleagues who put forward the role of the moved object (Grierson et al., 2013). Furthermore, it was shown that also the display of static pictures of specific phases of action has been proven to yield reliable estimation (Valenti & Costall, 1997). However, whatever the case, information related to the kinematics of movement, although deduced from static pictures, seems to be crucial in inferring the weight of the object. This effect was explained by subsequent neurophysiological researches showing that the difference in actor's kinematics, when lifting heavy and light objects, modulates the primary motor cortex excitability, and thus motor resonance (Alaerts, Senot, et al., 2010; Alaerts, Swinnen, et al., 2010; Rens et al., 2020).

On the basis of these results, and starting from the notion that sensorimotor expertise modulates motor resonance during action observation, one may hypothesize that individuals who developed specific ability in weight lifting can evaluate the weight of the object raised by an observed actor more accurately than non-experts given that the observed movement belongs to their motor repertoire.

Practice of several sports such as powerlifting and CrossFit® includes weightlifting and routinely requires a specific weight training. In powerlifting, athletes are engaged in lifting the maximum possible weight in three specific exercises: the back squat, the bench press and the deadlift (Kyle Travis et al., 2020). In CrossFit®, the training is organized in daily workouts including metabolic exercises, gymnastic movements and weightlifting, thus developing not only strength but also other physical components (Claudino et al., 2018) with a high catabolic impact (Faelli et al., 2020).

The purpose of this study was to investigate whether sensorimotor expertise influences the perceptual weight judgments during the observation of a sport-specific gesture. To this aim, we examined if expert athletes in executing the deadlift (powerlifters and CrossFit® practitioners) manifested higher ability in weight perception judgments than non-experts when observing this specific gesture performed by an athlete who lifted a barbell with different weights corresponding to different percentages of his 1 repetition maximum (1RM). Indeed, whilst it is known that motor resonance is differently modulated according to the individual’s sensorimotor expertise, the question concerning the role of motor resonance in evaluating the property of an object involved in an observed action deserves to be investigated. Powerlifters were enrolled due to their specific ability in the deadlift (Kyle Travis et al., 2020), while CrossFit® practitioners were recruited as this exercise is a part of their training program (Claudino et al., 2018). We hypothesized that the ability to judge the weight of a lifted load was higher in expert subjects than in naïve ones. Furthermore, considering the different level of expertise in the deadlift between powerlifters and CrossFit® practitioners, possible differences could arise between these two categories of expert athletes. We also considered possible differences among the conditions with different weights since, below the 1RM, participants with no experience in weight lifting can have more difficulties in estimating the observed weight than experts, whilst at 1RM the effort of the model might help them.

2.2. Materials and methods

2.2.1. Participants

An a priori power analysis was conducted using G*Power version 3.1.9.7 (Faul et al., 2007) to determine the minimum sample required to test the study hypothesis. The effect size was set at 0.25, considered to be medium using Cohen's criteria (Cohen, 1992). A F-test was applied with a significance criterion of $\alpha = 0.05$ and power = 0.80, the number of groups = 3, number of conditions = 3, the minimum sample size needed with this effect size was N = 36 for detecting differences in accuracy.

Fifty-six volunteers participated in the experiment. Based on their sport practice, participants were assigned to three groups: powerlifters (n=18; PL, 5 females and 13 males), CrossFit® practitioners (n=15; CF, 2 females and 13 males) and Controls (n=23, CTRL, 3 females, 20 males). The number of participants in the three groups was motivated by the opportunity we had in the recruitment process. The same reason explained why each sample had largely more males than females, a condition that possibly could influence the results, and for this reason could be a limitation of the study. In the Control group, subjects practiced no activities or activities not related to the weightlifting (Table 1). Furthermore, none of them reported having visual experience with deadlifts. All subjects were fully informed about the study aims and procedures and gave their informed consent. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee of the University of Genoa (Comitato Etico per la Ricerca di Ateneo, protocol n° 2021/42, date of approval 14/04/2021).

	Group			Statistical analysis
	Powerlifters	**CrossFit® practitioners**	**Controls**	
Number of subjects	18	15	23	--
Age (years)	33 ± 3	28 ± 1	31 ± 2	H(2)=4.15, p=0.13, η^2=0.04, 95%CI [-0.03-0.23][1]
Gender	Females (5) Males (13)	Females (2) Males (13)	Females (3) Males (20)	
Years of practice	5 ± 1	4 ± 1	-	U=103, p=0.24, r=0.21, CI [0.01-0.51][2]
Sports practiced	Powerlifting	CrossFit®	Fitness (3) Football (3) Running (2) Basketball (1) Cycling (1) Pilates (1) Rugby (1) Swimming (1) Thai boxe (1) No sport (9)	--
Deadlift 1RM (kg)	220 ± 10	161 ± 10	-	t(31)=3.65, p=.001[3], g=1.24, CI [0.49-1.97]
Level of performance	Agonists (14) Amateur (4)	Agonists (9) Amateur (6)	-	--

Table 1. Characteristics of participants. Data are mean ± SE, or as number of occurrences. 1RM = 1 Repetition Maximum. [1]Kruskal Wallis Test. [2]Mann-Whitney Test between powerlifters and CrossFit® practitioners. [3]Unpaired t-test between powerlifters and CrossFit® practitioners.

2.2.2. Experimental Paradigm

The experiment was built using jsPsych 6.3.0 library (de Leeuw, 2015). The experimental design included: a questionnaire, a video example, a familiarization phase and the experimental task. The questionnaire collected personal and sport-related data, such as activity performed, years of practice, deadlift 1 repetition maximum (1RM, for PL and CF) (Table 1). After completing the questionnaire, participants observed a video example showing a powerlifter executing a deadlift at 40%1RM. Then, a familiarization phase consisting of observing 6 videos, randomly chosen among those used in the experimental task and followed by relative questions, was performed. Familiarization trials were not included in the analysis. Although this kind of familiarization procedure was already adopted in all the experiments described in Auvray et al. studies on perceptual weight judgments (Auvray et al., 2011), one cannot exclude that it could have influenced the perception of the following movements. For this reason, it could be a limitation. Finally, participants executed the experimental task consisting of watching videos and answering the relative questions about the weight of barbell (Figure 1A).

2.2.3. Visual stimuli

The visual stimuli were videos showing a powerlifter executing a deadlift using the conventional technique, and with three different weights charged on the barbell. In the videos, the athlete acting as a model was a 25-years-old male powerlifter and certified trainer. The weights were determined starting from the maximum weight lifted by the athlete on shoot day, namely his 1RM, corresponding to the 100%1RM condition (210 kg). The other two weights corresponded to the 90%1RM (190 kg) and 80%1RM (167.5 kg) conditions. All videos were recorded on the same day with a recovery period between repetitions and lasted 5.0s (80%1RM), 5.6s (90%1RM) and 6.7s (100%1RM), respectively. During the execution of the deadlift, the model was filmed with a video-camera located in a lateral position so as to record the deadlift movement in the sagittal plane. The video-camera was mounted on a tripod (height about 1.20 m from the floor), positioned at a distance of about 1.60 m from the athlete (Figure 1B). To prevent participants from reconstructing the weight of the lifted load, and to avoid the size-weight illusion (Plaisier & Smeets, 2015), the biggest disc (corresponding to 25 kg), which determines the dimensions of the load visible by the participants, was present in each condition. Furthermore, to prevent participants from seeing how many discs were charged on the barbell, the discs were covered by a black plastic cover. At last, the athlete's face was blurred to mask his expressions during the deadlift. Videos used in the experiment are offered in the online Supplementary materials.

2.2.4. Experimental task

During the experimental task, participants observed the videos, sitting in front of the computer. Videos showing the lifting of each weight were displayed 16 times in a randomized order (3 weights x 16 times = 48 trials in total). Each video was followed by the question “Has he lifted the XX% of 1RM?”. Subjects were instructed to press as quickly possible the letter “v” for “Yes” answer and “n” for “No”. For each weight, in 8 of the 16 trials, the question asked to the participants mentioned the weight actually lifted by the athletes; thus, the correct answer was “Yes”. In the remaining 8 trials, the question mentioned the other two weights (4 times each), and thus the correct answer was “No”. The task duration was about 15 minutes. Participants took a pause after 24 trials (Figure 1C).

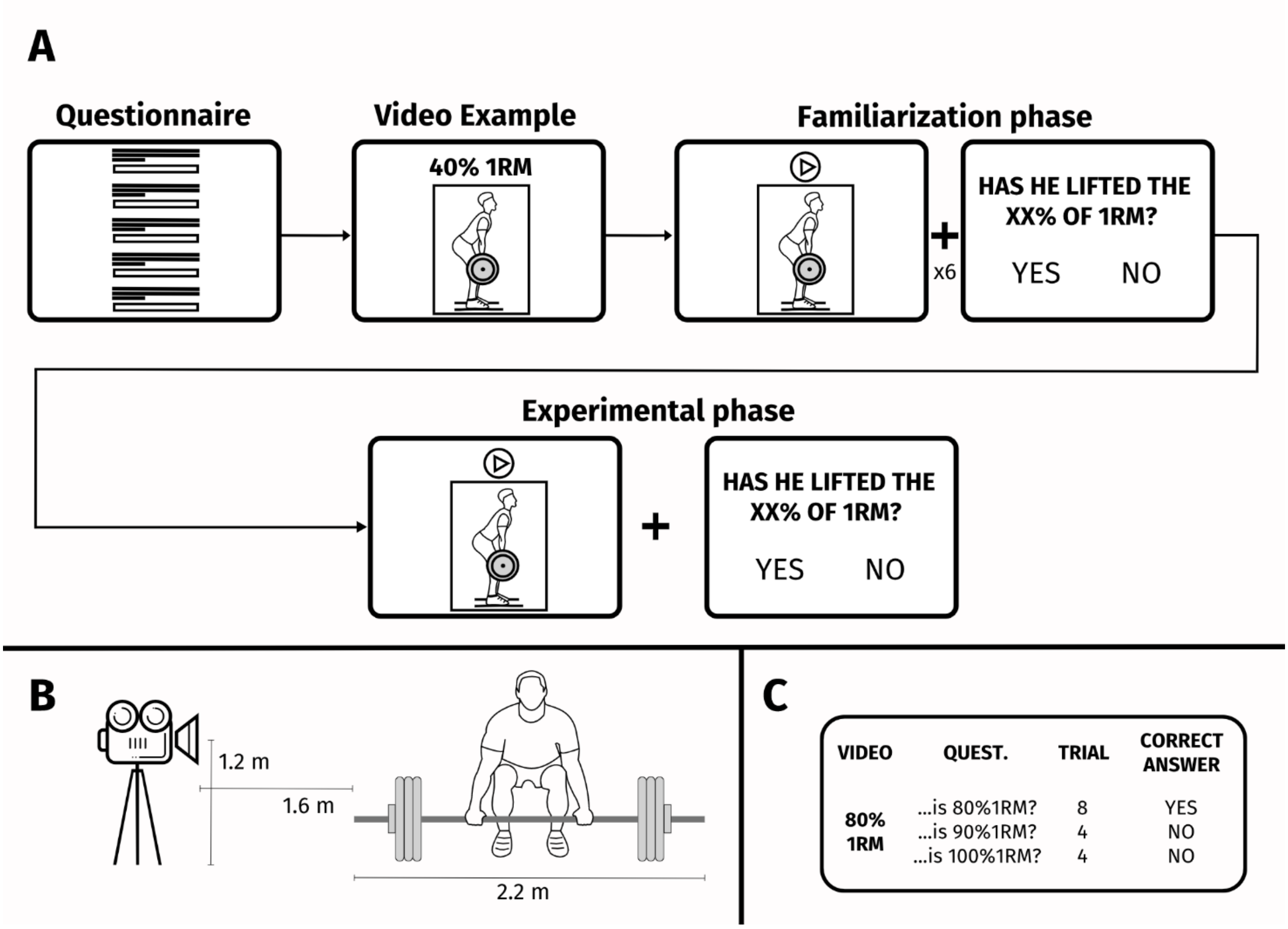

Figure 8. Experimental paradigm (A), set up (B) and task (C). (A) Each participant executed the experiment at computer. The participants filled a questionnaire that collected personal and sport-related data. After that, a video example of the deadlift was shown and a familiarization phase, consisting of 6 videos, was performed. Then, participants executed the experimental task. It consisted of 48 videos and a relative question about the magnitude of the weight lifted by the athlete. The videos showed a deadlift performed with three different weights corresponding to

80%, 90% and 100% of athlete's 1RM (16 videos/weight). After each video, the correct answer for each weight were 8 times "Yes" and 8 times "No". (B) Video-camera recorded from a lateral view the deadlift movement performed on the sagittal plane. (C) This figure represents an example of the questions asked to the participants (QUEST.), the number of repetitions for each question (TRIAL) and the correct answers when participants observed the video showing a weight corresponding to 80%1RM

2.2.5. Data analysis

The age of participants was compared by means of Kruskal-Wallis tests since it was not normally-distributed. PL and CF's years of practice and 1RM value were statistically evaluated between groups by means of Mann-Whitney tests.

The main outcome parameter used to evaluate participants' responses was accuracy, which was expressed as the percentage ratio of correct responses (both when the right answer was "Yes" and "No") to the total number of trials in 80%1RM, 90%1RM and 100%1RM. Furthermore, the coefficient of variation of the accuracy (CV) of each participant was also computed as the ratio between standard deviation and mean values on the three weight conditions.

Shapiro-Wilk test was applied to evaluate data distribution. Response accuracy was not-normally distributed, whilst the coefficient of variation was normally distributed. The within group analysis, aimed at evaluating the effect of the different percentage of weight (80%1RM, 90%1RM and 100%1RM) on response accuracy, was performed in each group by means of Friedman test, followed by post-hoc analysis. Kruskal-Wallis tests, followed by post-hoc analysis, was applied to compare the three groups (PL, CF and Controls) at each percentage of weight. For PL and CF, accuracy values were averaged across the three weight conditions and the resulting value were correlated with years of practice and 1RM values by means of Pearson correlation analyses. One-way ANOVA was applied on CV to evaluate the variability of the accuracy of participants in the three groups.

Normally distributed data are reported as mean values ± standard error (SE), while not-normally distributed data are given as median [interquartile range]. Statistical analyses were performed with SPSS Statistics 26 software. Significance level was set at 0.05. Effect sizes (η^2 for normally-distributed data and Kendall's test – W and r value for not normally-distributed data) and 95% Confidence Interval (CI) were reported.

2.3. Results

The Friedman test showed a significant effect of weight in every group. In PL (χ^2(2, 18) = 9.41, p = 0.009, W = 0.26, CI [0.07, 1.00]) post-hoc tests showed that accuracy at 80%1RM (87.5 [72.9, 100] %) was significantly higher than that at 90%1RM (58.3 [39.6, 75.0] %, p = 0.016). In CF (χ^2(2, 15) = 22.5, p < 0.0001, W=0.75, CI [0.69, 1.00]) the accuracy at 90%1RM (41.7 [29.2, 58.3] %) was significantly lower than that at 80%1RM (83.3 [75, 83.3] %, p = 0.0007) and at 100%1RM (76.7 [75.0, 83.3] %, p < 0.0001). In Controls (χ^2(2, 23) = 32.0, p < 0.0001, W = 0.70 CI [0.60, 1.00]) post-hoc analysis revealed that the accuracy at 90%1RM (41.7 [25-54.2] %) was significantly lower than that at 80%1RM (75 [58.3, 83.3] %, p = 0.0008) and at 100%1RM (75.0 [66.7, 83.3] %, p < 0.0001).

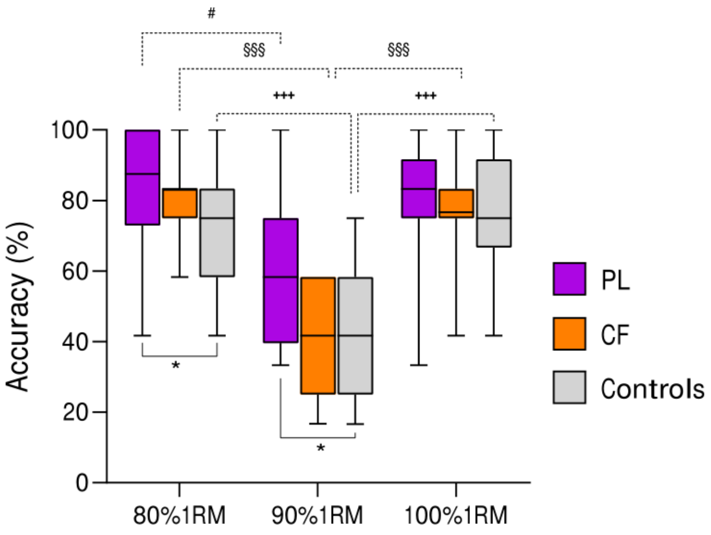

Figure 9. Response accuracy of powerlifters (PL, white box) and CrossFit® practitioners (CF, dotted box) and control participants (striped square) at the three percentages (80%, 90%, 100%) of the 1RM displayed in the videos. The box depicts median and the 25th and 75th quartiles. The whiskers show the 5th and 95th percentiles. * indicates a statistically significant difference between groups (p<0.05). The significant within group differences among weights are indicated by # (within PL), § (within CF) and + (within Controls). # p<0.05, §§§ and +++ p<0.001.

The between groups analysis performed by means of Kruskal-Wallis tests at each weight revealed a statistically significant effect of group at 80%1RM (H(2, 56) = 6.22, p = 0.045, η^2 = 0.08, CI [0.00-1.00]) and 90%1RM (H(2,56) = 7.68, p = 0.021, η^2 = 0.11 CI [0.01-1.00]). In both conditions, post-hoc tests showed that the PL had a significantly higher accuracy than Controls (80%1RM p = 0.041; 90%1RM p = 0.021). No significant differences emerged between PL and CF (80%1RM p = 1.0; 90%1RM p = 0.09), and CF and Controls (80%1RM = 0.50; 90%1RM p = 1.0). No GROUP effect was found at 100%1RM (p = 0.52) (Figure 9).

No significant correlations were found between mean accuracy values (PL 74.2±2.1; CF 66.0±2.6) and 1RM in both PL (R=-0.11, p=0.66) and CF (R=-0.24, p=0.39), as well as between accuracy and years of practice (PL: R=-0.40, p=0.07; CF: R=0.29, p=0.30).

The one-way ANOVA comparing CV values of the three groups (PL 0.29±0.03, CF 0.35±0.04; Controls 0.35±0.03) did not reveal a significant group effect (F(2, 53) = 1.04, p = 0.36, η^2 = 0.19).

2.4. Discussion

The aim of this study was to test the role of sensorimotor expertise in weight lifting in influencing the perceptual weight judgments during the observation of a sport-specific gesture. Results showed that only powerlifter were more accurate in evaluating the weight of the barbell with respect to non-experts. This difference was present when the weight lifted by the actor was below his 1RM, namely at 80%1RM and 90%1RM. No differences were found between PL and CF, and CF and Controls. Within groups, difference in the response accuracy were found among the different weights. No significant correlations were found between accuracy, 1RM and years of experience in deadlift. No differences among groups appeared in the coefficient of variation.

Results of the present study revealed that powerlifters, who had the highest and more specific expertise in deadlift, were more accurate in the perceptual weight judgments with respect to naïve participants. This was observed for weights below the 100%1RM, likely because the 100%1RM condition was markedly different from the other two conditions and the effort of the model appeared evident from his movement (see Videos in Supplementary materials). In this regards, Shim et al (Shim et al., 2004) showed that visual information concerning the effort that a model exerts influences the observer's weight perception, and thus might have helped also naïve participants to infer the weight in 100%1RM condition. In studies using action observation paradigms, the role of motor repertoire was already shown to be crucial for other perceptual capacities such as the recognition of the actor identity (Beardsworth & Buckner, 1981; Coste et al., 2021), the discrimination (Bidet-Ildei et al., 2010; Casile & Giese, 2006) and the anticipation of movement (Martel et al., 2011). The present findings add a piece of knowledge concerning the mechanisms underlying the object weight perception suggesting that motor resonance evoked in observer's played a crucial role. Indeed, when an individual observes an action in which she/he is an expert, the cortical motor system resonates with that action and a series of events, which influenced the following neurophysiological responses and behavioral performance, begin (Abreu et al., 2012; Balser, Lorey, Pilgramm, Stark, et al., 2014; Calvo-Merino et al., 2005, 2006; Wright et al., 2010).

In the sport domain, one of the most famous studies was that of Aglioti and colleagues (Aglioti et al., 2008), which showed that basketball players predicted the success of free shots at a basket earlier and more accurately than coaches and journalists and had a time-specific motor activation during observation of erroneous basket throws. These results were interpreted as a consequence of athletes' ability to read the body kinematic features, characteristics that only the athletes' motor system was endowed with. In two more recent studies, it was shown that the sensorimotor skills acquired by means of years of practice in swimming (Bove et al., 2017) and soccer (Pedullà et al., 2020) helped athletes to predict the final outcome of the task and to infer the observed action's long-term intention, respectively. Therefore, the possibility for the observers' motor system to match the kinematics of the observed movement with the own sensorimotor representation was shown to be crucial in sport domain to anticipate both the fate of an action and the action's intention.

The innovative feature of the present findings is that the link between action and its sensorimotor representation was pivotal to evaluate a property of the object (i.e., the weight) involved in the observed action, confirming the initial hypothesis of the study. Previous studies, not involving athletes or people with peculiar abilities, proposed that the kinematics features of the movement are central to help the observers to infer it (Alaerts, Senot, et al., 2010; Alaerts, Swinnen, et al., 2010; A. Hamilton et al., 2007; Antonia Hamilton et al., 2004; Rens et al., 2020). This is in line with the principle of kinematic specification of dynamics postulated by Runeson and Frykholm, which states that the kinematic patterns of events contain information about the dynamic properties, including the weight of manipulated objects (Runeson & Frykholm, 1981). Therefore, one might speculate that powerlifter, who developed a specific ability in deadlift, were better in judging the weight of the lifted load compared to naïve subjects thanks to their motor repertoire that includes the sensorimotor representation of this gesture. This highly detailed sensorimotor representation would allow PL to appreciate the subtle differences in performance model's kinematics that are at the basis of the recognition of the dynamic object's properties involved in the movement. It has to be noticed that this result could be motivated by the resonance evoked by the model, who was an experience powerlifter, in the observers who practiced Powerlifting. It has to be noticed that the results could have been different if the model in the video was a CrossFit® practitioner or a person naïve in deadlift.

Furthermore, one cannot exclude that the motor resonance evoked in PL directly reflects force requirements of observed lifting actions, as suggested by Valchev and colleagues (Valchev et al., 2015). At last, it cannot be ruled out that PL's perceptual experience influenced the results. Indeed, PL were used to perform, but also to observe other athletes performing the deadlift. This observational experience might have played a role in helping PL to evaluate the barbell weight. Whatever the case, the present results suggest that a specific sensorimotor expertise shapes motor resonance in such a way that the powerlifters gained the ability to judge the dynamic property of the objects involved in the observed movement.

The importance of having a specific ability in the observed gesture to be accurate in perceiving its features is further supported by the lack of difference between CF and Controls. In fact, while Powerlifting requires the athlete to perform a weight training over only three specific exercises such as the deadlift, the back squat and the bench press (Kyle Travis et al., 2020), CrossFit® includes within the same workout not only weight lifting training, but also metabolic and gymnastic exercises (Claudino et al., 2018). Hence, although deadlift is a part of CF's training, in Powerlifting the higher training specificity and the largest amount of time spent on the deadlift might explain why only PL's accuracy was better than that of Controls.

Contrarily to the initial hypothesis, no differences appeared in the response accuracy between the two categories of experts, namely PL and CF. Indeed, despite in each weight condition PL's accuracy was numerically higher than that of CF, and a not significant trend (p=0.09) appeared in 90%1RM, the differences were never significant. This lack cannot be attributed to the higher variability of one group with respect to the other, since the analysis of the coefficient of variation did not reveal any significant group effect. However, the variability of both groups was quite high as can be appreciated in Figure 2.

This might explain the lack of difference between PL and CF. Future studies might also consider to specifically assess the difference among the technical features of deadlift when performed by PL and CF and correlate this aspect with perceptual weight judgment ability.

Furthermore, no significant correlation was found between accuracy and the level of expertise, here quantified by means of 1RM value (which was significantly higher in PL than CF) and years of practice. This finding is in contrast with previous results showing that having a motor or visual expertise explained the different corticomotor responses of basketball players with respect to coaches/journalists during the observation of a basketball free shots (Aglioti et al., 2008). The years and weekly hours of practice influenced the way a specific tool (i.e., tennis racket and epee) was integrated within the athlete's peripersonal space (M. Biggio et al., 2017; M Biggio et al., 2020) and regulated the hand blink reflex within the defensive peripersonal space in boxers (Monica Biggio et al., 2019). To explain these divergent results with respect the literature we cannot rule out that 1RM and years of experience may not be the most sensitive parameters to quantify the level of experience in this sport skills. This is a limitation of the present study and future works might consider other variables, maybe most related to the technical features of the deadlift.

When considering the effects of different percentages of the lifted weight, the 90%1RM was, for every group, the hardest weight to distinguish. Indeed, in 90%1RM, PL's accuracy was significantly lower than that at 80%1RM, whilst the accuracy of CF and Controls was significantly lower than those at both 80%1RM and 100%1RM. An explanation could be that since the 90%1RM is the condition in between the other two (10% difference with both 80%1RM and 100%1RM), participants might have been confounded and partly misattributed the weight of the 90%1RM to 80%1RM and 100%1RM. To confirm this interpretation, it would have helped to ask participants not only to answer the question on the weight of the barbell, but, in case of negative answer, to request an estimate of the weight. Unfortunately, this data was not collected and thus represent a limitation of the present study.

2.5. Conclusions

This study shows, for the first time, the role that sensorimotor expertise, gained during years of sport practice has in evaluating the property and, in particular, the weight of the objects involved in the observed movement. A fine sensorimotor representation of the sport gesture seems crucial to detect small changes in the observed movement kinematics that we speculate are at the basis of the recognition of the objects' property. To go deeper into the mechanisms regulating the role of the sensorimotor expertise in object weight estimation, future studies will need to decouple the effect of the observation of the mere kinematics information of the model (for instance, using point-light display technique) and that of the lifted objet (Auvray et al., 2011; Grierson et al., 2013).

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Chapter 3. The role of ageing in discriminating the weight of an object during an action observation task

The ability to predict the weight of objects is important for skilled and dexterous manipulation during daily living. The observation of other people moving objects might represent an important source of information on object features and help to plan the own motor response. In aging, an impaired ability to evaluate the object weight might have negative drawbacks in term of the safety of the person. The aim of this study was to unveil the role of ageing in the ability to discriminate the object weight during action observation. Twenty elderly participants (Elderly) and 20 young adults (Young) performed a two-interval forced-choice task during which they observed a couple of videos showing an actor moving a box of different weights. The observer had to evaluate in which video the box was heavier. Handgrip strength was acquired. Sensitivity analysis was performed and psychometric curves were built on participants' responses. The results showed a diminished sensitivity in weight discrimination in Elderly than in YOUNG group. The analysis of the psychometric curves revealed that this impairment pertained both light and heavy boxes and that the minimum difference to discriminate different weights was greater in Elderly than in YOUNG. At last, the sensitivity and the discrimination ability significantly correlated with individuals' handgrip strength. These findings allowed to deeply characterize the impairments elderly have in discriminating the weight of an object moved by another individual.

3.1. Introduction

Instrumental activities of daily living (IADL) are complex activities of everyday life required to maintain the independence in the social life (Wang et al., 2020). IADL tasks include heavy household works as well as participating in cooperative task (Bowling et al., 2012; Edemekong et al., 2022). Examples of IADL that elders frequently experience are moving and receiving objects, such as a box or a shopping bag. In the latter circumstance, it is important to recognize the characteristic of the object to adopt the correct motor strategy and being ready to receive it safely (Mizuguchi et al., 2016). In particular, the ability to predict accurately the weight of objects is essential for skilled and dexterous manipulation, and the observation of the features of the movement of other people lifting objects might represent an important source of information (Reichelt et al., 2013).

Action observation studies showed that both the weight of the object involved in the action and the effort of the observed individual influenced the activity of the observer's sensorimotor brain areas (Alaerts, Senot, et al., 2010; Meulenbroek et al., 2007), suggesting that both characteristics are mapped into the individuals' sensorimotor representation. This information is then used to plan the following motor response, as suggested by Reichelt and collegueas, who showed that, after seeing the handling and the transfer of an object, the observer automatically adapted the lifting force to the weight of the observed object (Reichelt et al., 2013). An improper ability to evaluate the weight of the object might impair the individual during cooperative task and also have negative drawbacks in term of the safety of the person.

Whether aging impacts on the ability to obtain information about the weight of an object lifted by an actor was examined in a previous study (Maguinness et al., 2013), which showed, in older adults, impairments when observing small and light (less than 1kg) boxes, while no effect of aging was found for large and heavier (3 ÷18 kg) boxes. Since large boxes required full-body motion of the actor, authors claimed that these visual cues were more salient in term of information provided to the observer than that required to move the small boxes. However, the estimation ability was described only by the mean value of the sensitivity (*d'*) that, in case of large boxes, might have not been sufficiently sensitive. It could be possible that a more detailed analysis, taking into account the different weights, could be more informative. Since actions involving objects in this range of weight might cause the loss of the individual's stability, it is particularly important to pursue the matter.

Furthermore, although aging is associated with deterioration in visual motion perception that may impair the ability to process relevant motion cues (Billino et al., 2008; Insch et al., 2012), other aspects directly related to movement features might impact on the ability to discriminate the object weight. The decrease in muscle mass and strength in elderly people is a phenomena largely proved causing muscle weakness (Cruz-Jentoft et al., 2010; García-Hermoso et al., 2018; Rantanen et al., 2002; Wang et al., 2020). Since a number of studies showed that, during action observation, motor resonance mechanisms, namely the activation of the observer's sensorimotor system during action observation (G. Rizzolatti et al., 1999), occur and influence the way the individual perceives the observed action (Bisio et al., 2010, 2014; Calvo-Merino et al., 2006, 2010), one might hypothesize that the reduction of strength typical of physiological aging influences the evaluation of the weight of the object involved in the observed action. In line with this hypothesis, the effect of motor resonance on weight estimation was recently shown in a study of our group that examined the role of motor expertise in weight lifting on perceptual weight estimation ability (Previous Chapter).

The purpose of this study is to deepen the role of ageing in the ability to discriminate the object weight. To unveil this issue, a weight discrimination video task was proposed to a group of healthy young adults and a group of elderly adults, who were required to observe a video showing an actor performing an IADL task (i.e. lifting a box on a shelf). Results were correlated with handgrip strength to explore the role that muscle strength has in this ability.

3.2. Materials and Methods

3.2.1. Participants

Forty volunteers participated in the experiment. Depending on age, they were assigned to two groups, Elderly (n=20; male/females: 7/13; mean age ± SE=71 ± 2 years) and Young (n=20; males/female: 9/11; mean age ± SE=25 ± 1 years). Written informed consent was obtained from all participants before data collection. The study was approved by the ethical committee of the University of Genoa (Comitato Etico per la Ricerca di Ateneo, n° 2021/42) and was conducted in accordance with the Declaration of Helsinki.

3.2.2. Experimental procedure

The experiment consisted in a single session and included a strength measurement and weight discrimination video task. The strength (kg) of the participants was assessed with the KERN MAP handgrip dynamometer (KERN & SOHN GmbH). The participants performed the test in the standard position, sit on a chair, shoulder adducted and neutrally rotated, elbow flexed at 90° (Innes, 1999). The mean of three repetitions allowed to assess right and left handgrip strength (Innes, 1999). The mean between left and right handgrip strength was considered as the outcome parameter of Handgrip Strength (HS).

The weight-discrimination video task was built using jsPsych 6.3.0 library and performed off-line (de Leeuw, 2015). The task was preceded by the instructions, and by a questionnaire collecting personal data (i.e., gender, age, weight, height) and physical activity level (i.e., activities performed, year of experience, weekly hours of training) data. The protocol is represented in **Error! Reference source not found.**8A.

3.2.2.1. Video stimuli

The stimuli consisted in videos showing an actor performing an IADL; namely, the actor (either a woman or a man based on participant's gender, **Error! Reference source not found.**B) moved a box from the chest to a shelf over the head. The box was filled with varying amounts of sheets of paper in such a way as to assume 7 different weights (0, 2.5, 5, 7.5, 10, 12.5, 15 kg). Actors were informed about the weight of the box. Videos, whose durations range from 1.3s to 3.7s, were acquired in a same day with a video-camera positioned to record the execution of the lifting movement laterally. The face of the actor was blurred to cover facial expression.

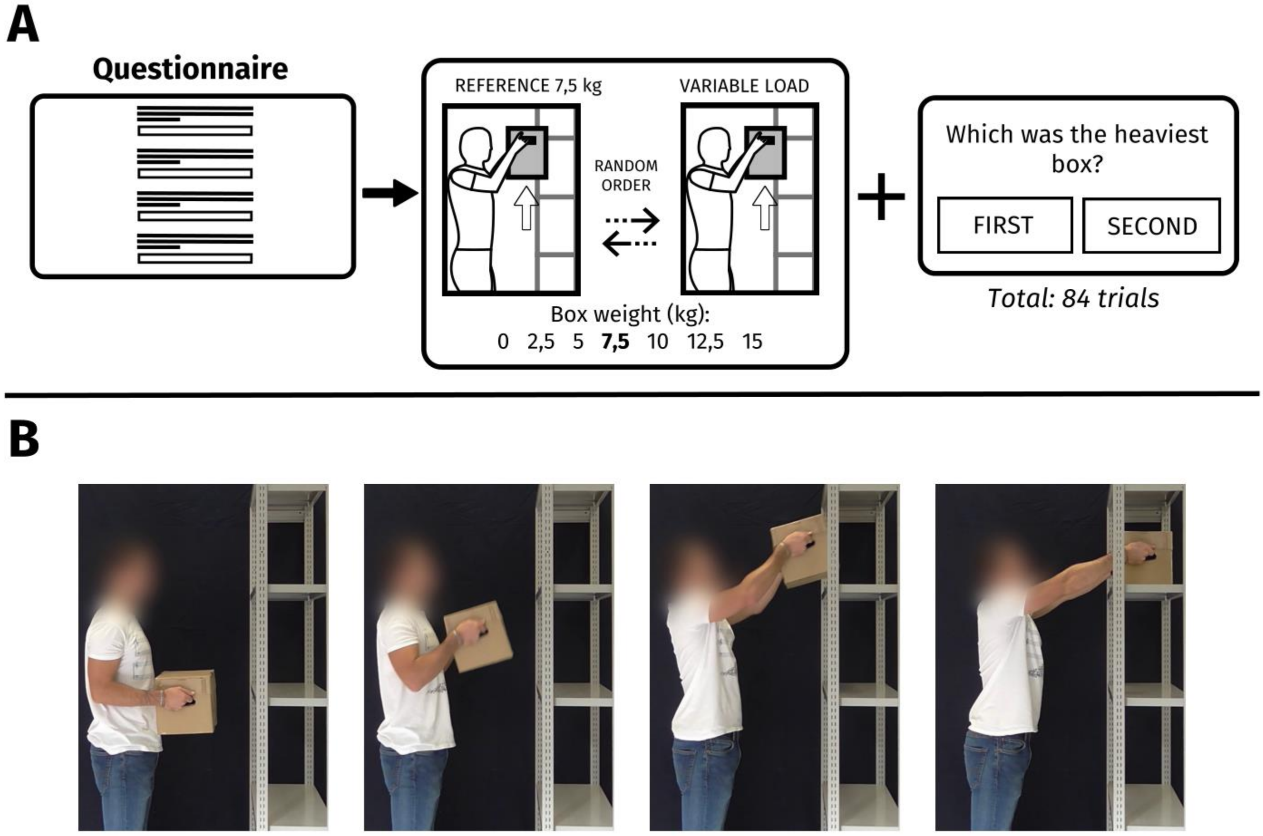

Figure 10. Experimental design. (A). Task Protocol: Each participant executed the task at computer. The participants filled a questionnaire collecting personal and physical activity related data. Then a two-interval forced-choice (2IFC) task consisted of 84 trials. Each trial contained two videos in sequence: one was the reference stimulus (box weight: 7.5 kg) and the other was one of the seven comparison stimuli (box weights: 0, 2.5, 5, 7.5, 10, 12.5, 15 kg). At the end a question asked in which video the box was heavier, and the participants could choose between “first” or “second”. (B) Frame of one video proposed participants.

3.2.2.2. Task

Participants seated in front of a laptop with a 16-inch LCD screen position on a table, at a distance of about 60 cm. They were required to perform a two-interval forced-choice (2IFC) task (Duarte et al., 2018). Each trial consisted in a sequence of two videos, a reference and a comparison stimulus. After the observation of both, the observer had to indicate in which video the box was heavier. In particular, the subject had to press the left arrow key to answer “First” and right arrow key to answer “Second”. The 7.5kg-video was showed every trial and represented the reference stimulus. The 0kg-, 2.5kg-, 5kg-, 7.5kg-, 10kg-, 12.5kg-, and 15kg-video were the comparisons stimuli (please notice that 7.5kg-video was used both as reference but also as comparison). In each trial, the order of appearance of the reference and the comparison stimuli was random. Each comparison video was displayed 12 times in random order, for a total number of trials corresponding to 84 (7 box weights, 12 repetitions). The total duration of the experiment was about 25 minutes.

3.2.3. Data analysis

The discrimination sensitivity (*d'*) was evaluated using signal-detection theory as described in Norman et al. (Norman et al., 2009). The higher *d'* values, the better the ability to discriminate between the object's weight.

The percentage of response in which the comparison stimulus was judge "Heavier" than the reference stimulus at each box weight was computed for each participant in the two conditions (Concentric and Eccentric). These proportions were used to build a Psychometric function. The observers' psychometric curves were obtained by finding the best-fitting logistic functions using *psyphy* and *quickpsy* R package (Linares & López-Moliner, 2016; Yssaad-Fesselier & Knoblauch, 2006). The lower and upper asymptotes, threshold, and just noticeable difference (JND), were estimated for each psychometric function (Knoblauch & Maloney, 2012). Lower asymptote (A_{LOW}) and upper asymptote (A_{UP}) were computed according to Oh et al. (Oh et al., 2016). The lower/higher A_{LOW}/A_{UP}, the better the ability to discriminate low/high weights. The threshold corresponds to the curve point crosses 0.5 on the y-axis and indicates the point of subject equality (Kopec & Brody, 2010). JND is considered as the smallest weight that produces changing in perception and calculated as the half difference between the weights at which the psychometric function equals to 0.75 and 0.25, respectively (von Sobbe et al., 2021). A lower JND indicated a better ability to discriminate the stimuli.

3.2.4. Statistical analysis

The Handgrip Strength (HS), sensitivity (*d'*) at each comparison stimulus (Norman et al., 2009), mean sensitivity (*mean d'*) (Maguinness et al., 2013), Heavier probability at each box weight, A_{LOW}, A_{UP}, threshold, and JND, were considered as outcome parameters. Shapiro-Wilk test was applied to evaluate data distribution and Levene's test was used to evaluate the equality of variances. HS, and *mean d'* were normally distributed, whilst *d'*, Heavier probability, A_{LOW}, A_{UP}, threshold, and JND, were not.

Left and right HS were statistically evaluated by means of a repeated measure ANOVA with GROUP as between subject factor (2 levels: Yong and Elderly), and SIDE as within subject factor (2 levels: Right and Left). Then, since the task displayed in the video was a bimanual task, left and right HS were averaged in the following analyses.

Concerning the sensitivity analysis, Mann-Whitney tests were applied to compare d' values at each comparison stimulus between groups. Then, a t-test was performed to statistically compare *mean* d' between Young and Elderly. Pearson correlation was applied to test the relationship between HS and *mean* d' on data from both groups pooled together.

Concerning the psychometric function, Heavier probability at each box weight was compared between groups by means of Mann-Whitney test. The not-normally distributed data derived from the curve were statistically evaluated by means of Mann-Whitney test with the aim to compare the two groups, and Wilcoxon test to assess differences between conditions within each group. Spearman correlations were applied to assess the relationship between HS and threshold, JND, A_{LOW}, A_{UP} on data from both groups pooled together.

Normally distributed data are reported as mean value ± standard error (SE), while not-normally distributed data are given as median [interquartile range, IQR]. Significance level was set at 0.05. Statistical analyses were performed with SPSS Statistics 26 software.

3.3. Results

3.3.1. Handgrip strength

The ANOVA applied to compare HS between two groups revealed a significant main effect of GROUP (F(1,38)=4.18, p=0.048, η^2=0.096), indicating that HS in Young (32.3±1.0 kg) was significantly higher than in Elderly (23.3±1.2 kg). A significant main effect of SIDE was also found (F(1,38)=14.42, p=.00005, η^2=0.01), and Right HS (30.1±1.2 kg) was significantly higher than Left HS (28.1±1.1 kg).

3.3.2. Sensitivity analysis (d')

Mann-Whitney tests showed that *d'* values were significantly higher in Young than in Elderly group at 0 kg (Elderly: 2.77 [1.50, 3.46]; Young: 3.46 [3.46, 3.46]; U=110, z=-2.69, p=0.014), 2.5 kg (Elderly: 1.93 [0.86, 3.29]; Young: 2.77 [2.77, 3.46]; U=123, z=-2.15, p=0.038) and at 15 kg (Elderly: 1.35 [0.98, 2.77]; Young UNG: 2.77 [2.14, 3.29]; U=119.50, z=-2.22, p=0.028) (Figure 2A). The statistical analysis on *mean d'* showed a significant difference between groups (t(38)=3.18, p=0.003, d=1) indicating that *d'* was higher in Young group (2.45±0.12) than in Elderly group (1.77±0.18) (**Figure 11**B). A significant positive correlation was found between HS and *mean d'* in (r(38)=0.47, p=0.0023) (**Figure 11**C).

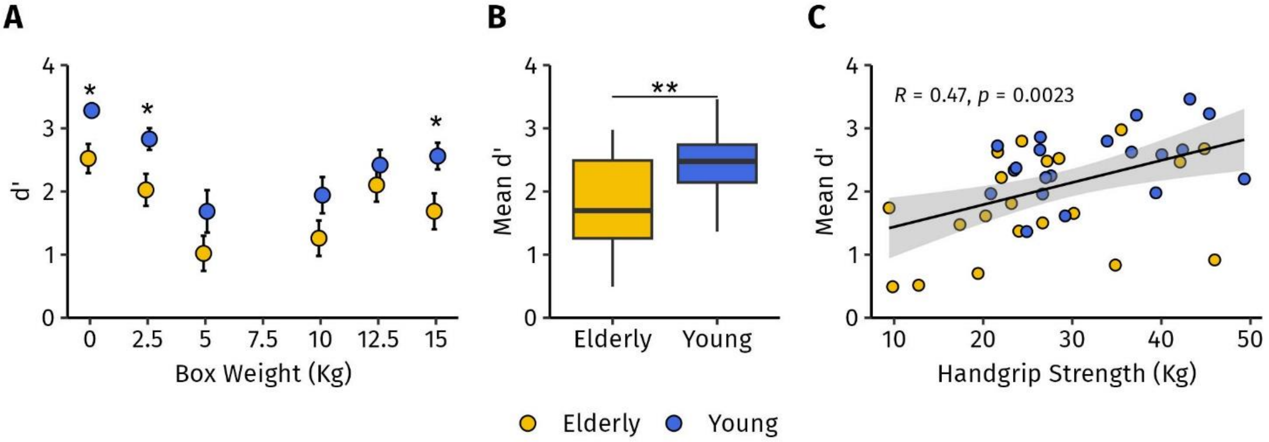

Figure 11. (A) Discrimination sensitivity (d') for Elderly (yellow) and Young (blue) groups. at each weight. (B) Mean d' between groups. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. (C) Correlations between Handgrip Strength and d' in Concentric condition. Each dot represents the d' value as function of Handgrip Strength for each participant for Elderly (yellow) and Young (blue). R is correlation coefficient and p the significance level of the test. *p < 0.05, ***p < 0.001.

3.3.3. Weight discrimination ability

The graphical representation of the psychometric functions of the two groups is displayed in **Figure 12**A.

The comparison between Heavier probability at each box weight showed a significant main effect of GROUP at 0 kg (Elderly: 0.08 [0.00, 0.17]; Young: 0.00 [0.00, 0.00]; z=-2.94, p=0.003), at 2.5 kg (Elderly: 0.17 [0.06, 0.27]; Young: 0.08 [0.00, 0.08]; z=-2.24, p=.025), and at 15 kg (Elderly: 0.83 [0.75, 0.92]; Young: 0.92 [0.90, 0.94]; z=-2.35, p=0.019).

The result of the statistical analysis on A_{LOW} showed that it was significantly higher in Elderly (0.08 [0.00, 0.19]) than in Young (0.00 [0.00, 0.03]) (U=115, z=-2.49, p=0.021) (**Figure**

12B) Young's A_{UP} was significantly higher than that of Elderly (U=120, z=-2.36, p=0.02; Elderly 0.86 [0.83, 0.94]; Young 0.95 [0.90, 0.99]) (**Figure 12**C).

Concerning the threshold, no difference between groups was found (Elderly: 8.07 [6.59, 9.39] kg; Young: 7.51 [7.34, 7.66] kg). JND value was significantly higher in Elderly (3.31 [1.77, 4.41] kg) than in Young (1.67 [0.31, 2.52] kg) (U=107, z=-2.53, p=0.010) (**Figure 13**A). Spearman's rank correlation, computed to assess the relationship between HS and JND, showed a significant negative correlation (r(38)=-0.5, p=0.0011) (**Figure 13**B).

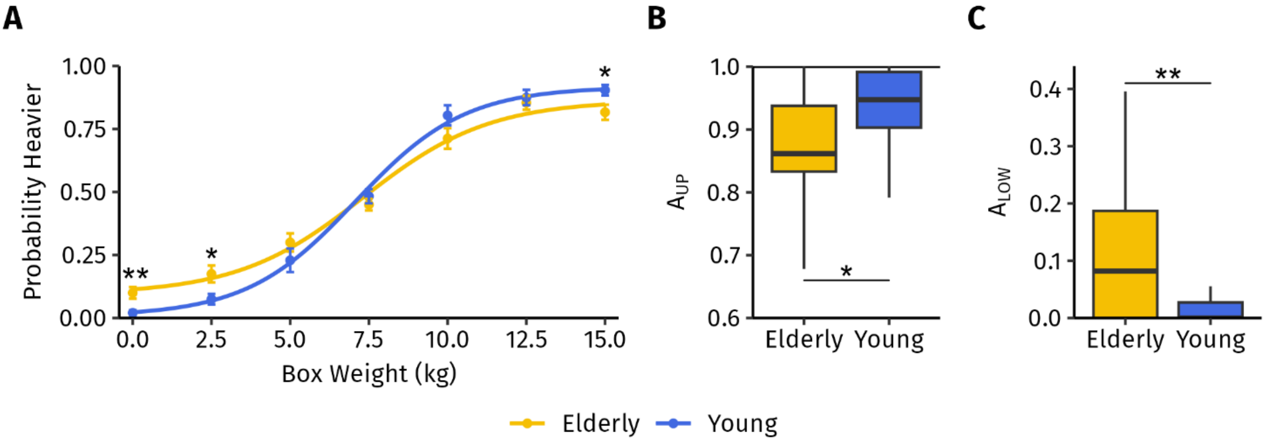

Figure 12. (A) Psychometric functions for Elderly (yellow) and Young (blue) groups. Dots represent the proportion of Heavier responses at each load for each group, obtained from the average of the responses of all participants to each load. (B) Lower Asymptotes (ALOW) and (C) Upper Asymptotes (AUP) and for Elderly (yellow) and Young (blue) groups. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. *p < 0.05, **p < 0.01.

3.4. Discussion

The results of this study showed that human ability to discriminate the weight of a box moved by an actor significantly deteriorates due to ageing for different amount of weight. In particular, after confirming the literature showing a general diminished sensitivity for discriminating the weight with respect to young adults (analysis on *mean d'*), the analysis on *d'* and on the psychometric curves allowed for better characterization of this

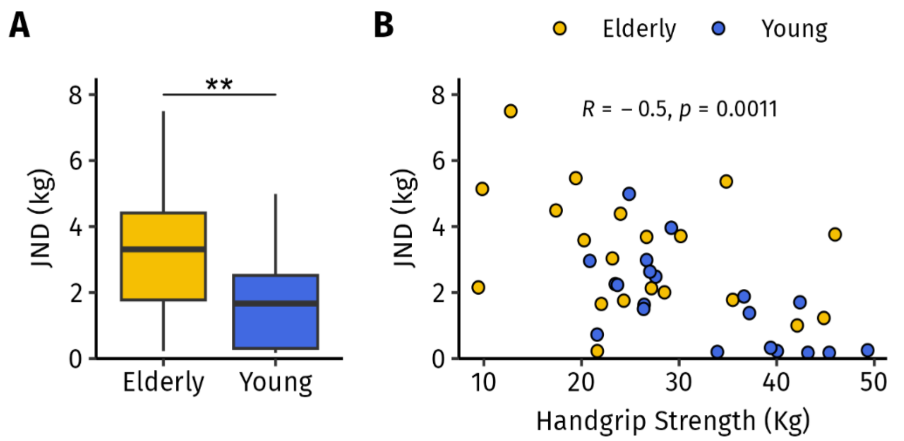

Figure 13. (A) Just Noticeable Difference (JND) for Elderly (yellow) and YOUNG (blue) groups. The black horizontal line indicates, the box represents the inter-quartile ranges, and the bars show the maximum and minimum value. (B) Correlations between Handgrip Strength and JND. Each dot represents the JND value as function of Handgrip Strength for each participant for Elderly (yellow) and Young (blue). R is correlation coefficient and p the significance level of the test. $^*p < 0.05$, $^{***}p < 0.001$.

phenomenon for different amount of weight. In particular, the analysis on *d'* at the different weights showed that elderly's sensitivity was significantly lower than those of young adults for both light (0 and 2.5 kg) and heavy (15 kg) boxes. In agreement with this result, the point-by-point analysis of the psychometric functions showed that elderly's discrimination ability was lower than that of young adults in correspondence of the same weights. Impairments in weight discrimination for both light and heavy boxes are confirmed by the analysis of the asymptotes of the curve, which give information about the ability to discriminate extremely low and high weights. Indeed, the values of the lower asymptote (providing information about the ability to judge light boxes) were higher for Elderly than for Young, whilst the value of the upper asymptote (providing information about the ability to judge heavy boxes) was lower for Elderly than for YOUNG. Furthermore, JND values were significantly higher in Elderly than in Young, suggesting that the minimum difference to discriminate different weights was greater in the elderly population than in young adults. At last, the correlation analyses showed that the discrimination ability evaluated by means of *mean d'* and JND significantly correlated with individuals' handgrip strength.

The results described by the sensitivity analysis on *mean d'* are in line with those of the literature exploring the effects of ageing on weight discrimination, and showed that elderly's sensitivity for discriminating the different weights is impaired with respect to that of young adults (Maguinness et al., 2013; Norman et al., 2009; Watson et al., 1979). This finds confirmation in the JND parameter resulting from the psychometric curves, whose values in elderly were about twice as much as those of young participants, indicating that, for this kind of movement, the minimum difference to discriminate the weight of two moving objects is higher in the elderly population.

The results of sensitivity analysis at the different weights and of the psychometric analysis add new insight on this matter. First, it was possible to describe what happened for different amount of weight. For both light and heavy boxes, d' was worse in elderly than in young adults. This was confirmed by the point-by-point analysis of the psychometric functions and the analysis on the curve asymptotes, which revealed that differences in the accuracy of the response were found for both light and heavy boxes. This result is at odds with those described in Maguiness and colleagues' study (Maguinness et al., 2013). In that work, authors failed to find differences in *mean* d' between elderly and young adults when showing the lifting of a large box, the weight of which ranged from 3 to 18 kg. The box displayed in the present study was quite similar in dimensions to that used in the "large box condition" of Maguiness et al.'s work and the highest weight, namely 15 kg, is in the range of weight they used. However, authors did not test d' at the different weights within the range. Therefore, one cannot exclude that their results would have been different if a point-by-point analysis had been performed.

Having a detailed description of what happened for different weights is particularly relevant to be considered in case of heavy objects. Indeed, during cooperative tasks it is common to receive objects from a companion. To do it efficiently and safely, our brain extrapolates the information from the companion's motion and use it to scale forces to cope with the expected load (Reichelt et al., 2013). If the mechanisms involved in weight estimation is impaired, the individual could adopt an inappropriate motor strategy, making the interaction less effective and putting the own neuromuscular system integrity at risk.

It is known that movement perception triggers motor resonance mechanisms, namely the activation of the perceiver's sensorimotor system when observing someone else actions (G. Rizzolatti et al., 1999). In turn, this mechanism is influenced by the own sensorimotor experience that models the way the individual perceives the external word (Aglioti et al., 2008; Bisio et al., 2010; Petroni et al., 2010). The difficulty for the observer to create a direct match (G. Rizzolatti et al., 2001) between the own motor repertoire and the observed action might thus be deteriorated by the different sensorimotor capacities of the actor and the observer. This might negatively affect the perception of the kinematic features of the observed movement that underlies object weight estimation (Alaerts, Senot, et al., 2010; Alaerts, Swinnen, et al., 2010). In the present study, elderly participants had a significantly lower handgrip strength with respect to young adults. This parameter was shown to influence participants' ability to discriminate the weight of the moved object. In particular, a positive correlation appeared between handgrip strength and *mean d'*, suggesting that individuals who developed higher force were those with a higher sensitivity in discriminating the observed object weight. In agreement, the negative correlation between HS and JND indicates that the least noticeable difference between two weights decreased with increasing strength. Therefore, one might conclude that the higher the strength of the individual, the better the ability to discriminate the object weight during an action observation task.

To explain the differences between groups one cannot exclude the contribution of other factors. Healthy ageing is characterized by a decline in the neural system that pertains both central and peripheral regions of the nervous system, causing impairments in motor control and in movement perception (Hunter et al., 2016; Seidler et al., 2010). In particular, at peripheral level, the proprioceptive receptors, in charge of sending to the brain information related to the sense of position, strength and heaviness (Proske & Gandevia, 2012), undergo anatomical and physiological changes during ageing that cause a deterioration of the proprioceptive afferences (Goble et al., 2009; Shaffer & Harrison, 2007). This altered input reaches the sensorimotor brain regions that, in turn, suffer from ageing, resulting in proprioceptive dysfunctions (Goble et al., 2009). All these physiological changes, known to contribute to a decline in motor control (Seidler et al., 2010), might have negatively affected also motion perception (Roudaia et al., 2010). Furthermore, deterioration in the processing of biological motion displays (Billino et al., 2008; Insch et al., 2012; Pilz et al., 2010) and in the sensitivity to changes in the speed of a moving stimuli present with ageing (Conlon & Herkes, 2008) have been called into question. At last, the brain regions involved in weight perception in both frontal and parietal lobules (A. F. d. C. Hamilton et al., 2006) are known to undergo to progressive deterioration in aging that can explain these findings (Seidler et al., 2010).

3.5. Conclusion

In conclusion, the present findings suggest that the ability to discriminate the weight of an object moved by another person is impaired in aging for both light and heavy objects. This ability depends on the force the individual is able to express. Since the ability to estimate the weight of a moved object can influence the individual's daily life activity, one might suggest that working on strength training can be beneficial not only to improve movement execution but also in perceptual task, such as object weight estimation.

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Chapter 4. The role of movement type in discriminating the weight of an object during an action observation task

4.1. Introduction

Starting from the discovery of the mirror neuron system, a huge amount of studies concluded that a common representation for human movement execution and perception exists (Bonini et al., 2022). Scientific literature refers to this mechanism naming it motor resonance, that consists in the activation of the perceiver's motor system when observing human movement (Rizzolatti et al., 1999). In a recent review paper, the author made the points on which are the factors modulating the mirror neuron system activity during action observation (Kemmerer, 2021). Some of them are specifically related to the features of the observed movement and the possibility for them to be mirrored into the observer's motor repertoire. For instance, a stimulus moving according to the biological laws of motion can be mapped into the observer's motor programs (Bisio et al., 2010, 2012, 2014); the observation of a specific motor skill will activate motor resonance if owned also be the observe (Aglioti et al., 2008; Calvo-Merino et al., 2005, 2006). Therefore, the way humans perceive the external movement is shaped by their motor repertoire. Thus, if differences are present between two kinds of movements, it is likely that these differences influenced movement perception.

Human movements are characterized by both concentric (i.e., muscle is contracted and shortens, such as the upward phase of a biceps curl) and eccentric (i.e., muscle is contracted and lengthens, such as the lowering phase of a biceps curl) muscle contractions. Scientific literature provides several evidence concerning the difference between these kinds of contractions (Duchateau & Baudry, 2014). For instance, maximal voluntary force is higher in eccentric than concentric contractions, as well as force fluctuations (Christou & Carlton, 2002; Fang et al., 2001; Grabiner & Owings, 2002; G. H. Yue et al., 2000), while the electromyogram (EMG) amplitude is either similar or bigger (Duchateau & Baudry, 2014). A higher risk of injury was documented during eccentric than concentric contractions (Shellock et al., 1991). The differences pertain also cortical activation (Kwon & Park, 2011; Winstein et al., 1997; G. Yue & Cole, 1992). Indeed, several lines of evidence pointed to different cortical mechanisms in the execution of concentric and eccentric contractions. In particular, during eccentric contractions, greater cortical activity was detected through a fMRI investigation in the right inferior parietal lobe, the pre-supplementary motor area, the anterior cingulate cortex, the right prefrontal, and the left cerebellar hemisphere (Kwon & Park, 2011), whilst a greater BOLD signal intensity was observed in the left primary motor cortex and the right cerebellum and vermis during the execution of concentric contractions (Howell et al., 1995). Differences between these kinds of movements were found in the primary motor cortex activity also during the preparation phase. Canepa and colleagues showed a time-specific modulation of corticospinal excitability in the preparatory phase to an eccentric muscle contraction (Canepa et al., 2021).

In light of all these differences, and based on the motor resonance theory, one might hypothesize that differences could be present when an individual observes an eccentric and a concentric muscle contractions and then is required to judge its features, such as the weight of the moved object.

The aim of this study was to test if the ability to discriminate the weights of objects moved by an actor changed during eccentric or concentric contractions.

4.2. Materials and Methods

4.2.1. Participants

Thirty-five volunteers (male/females: 11/24; mean age ± SE=24.7±0.8 years) participated in the experiment. Written informed consent was obtained from all participants before data collection. The study was approved by the ethical committee of the University of Genoa (Comitato Etico per la Ricerca di Ateneo, n° 2021/42) and was conducted in accordance with the Declaration of Helsinki.

4.2.2. Experimental procedure

The experiment consisted in a single session where participants performed a weight discrimination video task. The task was built using jsPsych 6.3.0 library and performed off-line (de Leeuw, 2015). The task was preceded by the instructions, and by a questionnaire collecting personal data (i.e., gender, age, weight, height) and physical activity level (i.e., activities performed, year of experience, weekly hours of training) data. The protocol is represented in Figure 14A.

4.2.2.1. Video stimuli

The stimuli consisted in videos showing an actor performing an IADL; namely, the actor (either a woman or a man based on participant's gender, Figure 14B) moved a box from the chest to a shelf over the head (Concentric condition, given that the main muscle involved in the movement, i.e., the anterior deltoids, shortened in this kind of movement – based on preliminary EMG acquisitions) or bring it down from the shelf to the chest (Eccentric condition, given that the deltoids anterior lengthened). In both conditions, the box was filled with varying amounts of sheets of paper in such a way as to assume 7 different weights (0, 2.5, 5, 7.5, 10, 12.5, 15 kg). Actors were informed about the weight of the box. Videos, whose durations range from 1.3s to 3.7s, were acquired in a same day with a video-camera positioned to record the execution of the lifting movement laterally. The face of the actor was blurred to cover facial expression.

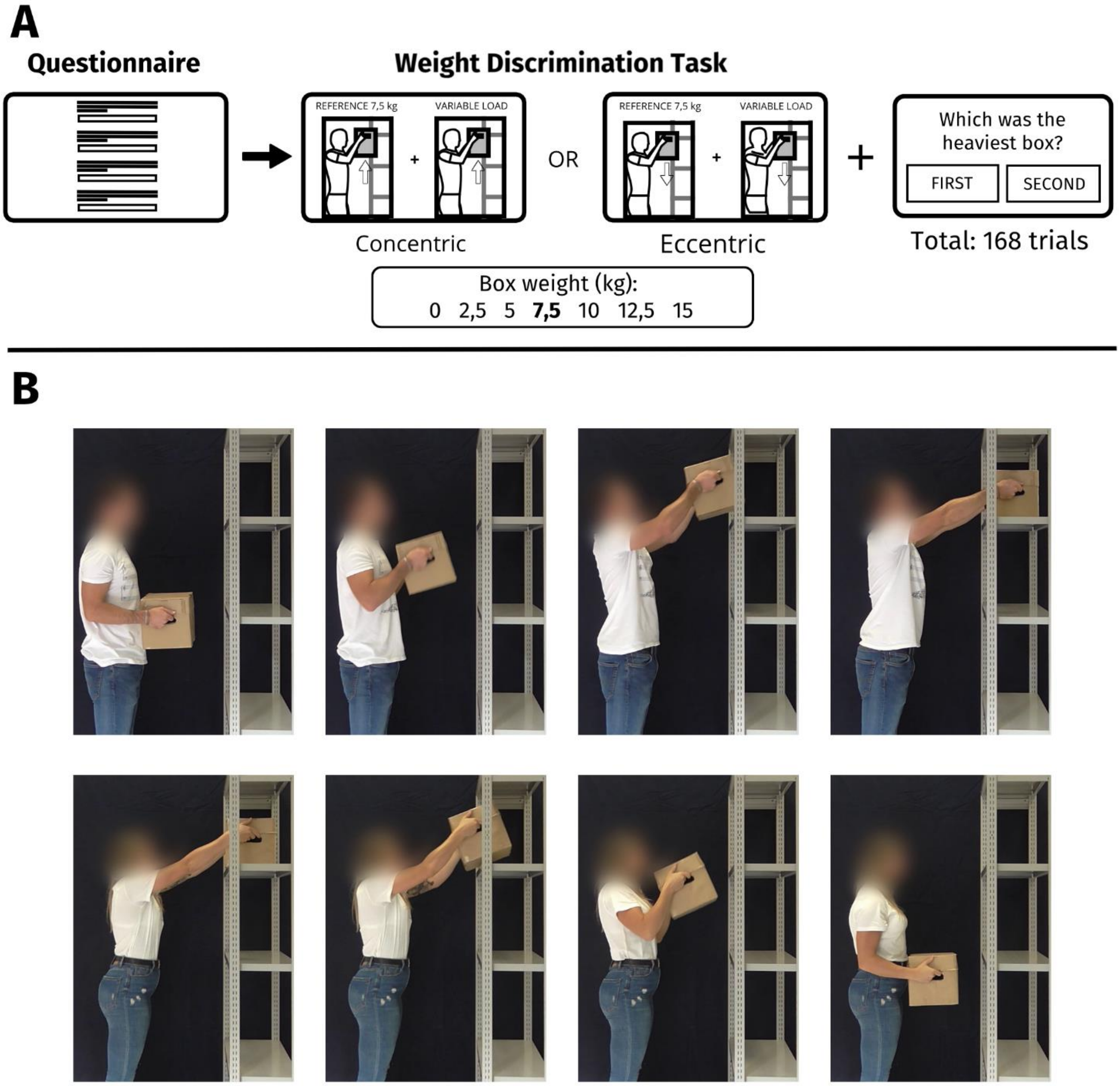

Figure 14. Experimental design. (A). Task Protocol: Each participant executed the task at computer. The participants filled a questionnaire collecting personal and physical activity related data. Then a two-interval forced-choice (2IFC) task consisted of 84 trials. Each trial contained two videos in sequence: one was the reference stimulus (box weight: 7.5 kg) and the other was one of the seven comparison stimuli (box weights: 0, 2.5, 5, 7.5, 10, 12.5, 15 kg). At the end a question asked in which video the box was heavier, and the participants could choose between “first” or “second”. (B) Frame of one video proposed participants for male and female.

4.2.2.2. Task

Participants seated in front of a laptop with a 16-inch LCD screen position on a table, at a distance of about 60 cm. They were required to perform a two-interval forced-choice (2IFC) task (Duarte et al., 2018). Each trial consisted in a sequence of two videos, a reference and a comparison stimulus. After the observation of both, the observer had to indicate in which video the box was heavier. In particular, the subject had to press the left arrow key to answer "First" and right arrow key to answer "Second". The 7.5kg-video was showed every trial and represented the reference stimulus. The 0kg-, 2.5kg-, 5kg-, 7.5kg-, 10kg-, 12.5kg-, and 15kg-video were the comparisons stimuli (please notice that 7.5kg-video was used both as reference but also as comparison). In each trial, the order of appearance of the reference and the comparison stimuli was random. Each comparison video was displayed 12 times in random order for each condition, for a total number of trials corresponding to 168 (7 box weights, 12 repetitions, 2 conditions). The total duration of the experiment was about 30 minutes.

4.2.3. Data analysis

The discrimination sensitivity (*d*') was evaluated using signal-detection theory as described in Norman et al. (Norman et al., 2009). The higher *d*' values, the better the ability to discriminate between the object's weight. Then data were classified as Light (0kg, 2.5kg, 5kg) and Heavy (10kg, 12.5, 15kg) and *LHmean d*' was obtained in the two conditions. At last, *mean d*' computed taking into account all weights were computed.

The ratio of response in which the comparison stimulus was judge "Heavier" than the reference stimulus at each box weight was computed for each participant in the two conditions (Concentric and Eccentric) to build a Psychometric function. The observers' psychometric curves were obtained by finding the best-fitting logistic functions using *psyphy* and *quickpsy* R package (Linares & López-Moliner, 2016; Yssaad-Fesselier & Knoblauch, 2006). The lower and upper asymptotes, threshold, and just noticeable difference (JND), were estimated for each psychometric function (Knoblauch & Maloney, 2012). Lower asymptote (A_{LOW}) and upper asymptote (A_{UP}) were computed according to Oh et al. (Oh et al., 2016). The lower/higher A_{LOW}/A_{UP}, the better the ability to discriminate low/high weights. The threshold corresponds to the curve point crosses 0.5 on the y-axis and indicates the point of subject equality (Kopec & Brody, 2010). JND is considered as the smallest weight that produces changing in perception and calculated as the half difference between the weights at which the psychometric function equals to 0.75 and 0.25, respectively (von Sobbe et al., 2021). A lower JND indicated a better ability to discriminate the stimuli.

4.2.4. Statistical analysis

Sensitivity (*d'*) at each comparison stimulus (Norman et al., 2009), mean sensitivity (*mean d'*, obtained by averaging *d'* at the different comparison stimuli except 7.5-kg) (Maguinness et al., 2013), A_{LOW}, A_{UP}, threshold, and JND, were considered as outcome parameters. Shapiro-Wilk test was applied to evaluate data distribution and Levene's test was used to evaluate the equality of variances. LH*mean d'* and *mean d'* were normally distributed, whilst *d'*, A_{LOW}, A_{UP}, threshold, and JND were not.

Concerning the sensitivity analysis, Wilcoxon tests were applied to compare *d'* values at each comparison stimulus between Concentric and Eccentric conditions. Within each condition, Friedman tests, followed by post hoc, was used to assess differences among *d'* at each comparison stimulus (0kg, 2.5kg, 5kg, 10kg, 12.5kg, and 15kg). An ANOVA was applied on *LHmean d'* with Amount-of-weight (2 levels, Light and Heavy) and Condition (2 levels, Concentric and Eccentric) as within subject factors. Then, a t-test was performed to statistically compare *mean d'* between Concentric and Eccentric conditions.

Concerning the psychometric function, all parameters were statistically evaluated by Wilcoxon test to assess differences between the two conditions.

Normally distributed data are reported as mean value ± standard error (SE), while not-normally distributed data are given as median [interquartile range, IQR]. Significance level was set at 0.05, except for *d'*, where Bonferroni correction (p=0.05/2=0.025) was applied due to multiple comparisons. Statistical analyses were performed with SPSS Statistics 26 software.

4.3. Results

4.3.1. Sensitivity analysis (d')

The results of the Wilcoxon tests on d' showed that significant differences between Concentric and Eccentric conditions appeared at 2.5kg (Z=-2.80, p = 0.005), 5kg (Z=3.23, p=0.001) and 10kg (Z=-2.36, p=0.018). No difference was observed at 0kg, 12.5kg and 15 kg (p>0.025) between the two conditions. Friedman test showed a significant effect of weight in both Concentric ($\chi^2(5)=28.0$, p<0.0001) and Eccentric ($\chi^2(5)=66.9$, p<0.0001) conditions. In Concentric condition, the post hoc analysis revealed that d' at 0kg was significantly higher than at 5kg (p<0.0001), 10kg (p=0.003) and 12.5kg (p=0.005). In Eccentric Condition, the post hoc showed that d' at 0kg was significantly higher than at 10kg (p<0.0001), 12.5kg (p=0.001) and 15kg (p=0.008). Furthermore, d' at 2.5kg was significantly higher than at 10kg (p<0.0001), 12.5kg (p=0.002) and 15kg (p=0.019). At last, d' at 5kg was significantly higher than 10kg (p<0.0001). Data are given in Table 2 and represented in Figure 15A.

d' values	**0kg**	**2.5kg**	**5kg**	**10kg**	**12.5kg**	**15kg**
Concentric	3.46 [2.77, 3.46]	2.77 [1.93, 3.46]	1.93 [0.86, 3.46]	1.93 [1.35, 3.46]	2.77 [1.35, 3.46]	2.77 [2.35, 3.46]
Eccentric	3.46 [2.77, 3.46]	3.46 [2.77, 3.46]	2.77 [2.35, 3.46]	1.35 [0.86, 2.35]	1.93 [1.35, 2.77]	2.77 [1.93, 2.77]

Table 2. Discrimination sensitivity (d’) at each weight and condition. Data are expressed as median [interquartile range].

ANOVA performed on *LHmean* d' showed a significant Amount-of-weight effect (F(1,34)=26.1, p<0.001, $\eta^2=0.20$) and a significant interaction Condition*Amount-of-weight (F(1,34)=32.9, p<0.001, $\eta^2=0.16$). In Eccentric condition, post hoc analysis revealed that *LHmean* d' was significantly higher in Light than in Heavy (Light: 3.04 ± 0.06, Heavy: 2.03 0.126; p<0.001). No difference was found between Light and Heavy in Concentric condition. In Light, participants had a higher *LHmean* d' in Eccentric than Concentric condition (Concentric: 2.55±0.11, Eccentric: 3.04±0.06; p<0.0001). The opposite was observed in Heavy where *LHmean* d' was higher in Concentric than in Eccentric condition (Concentric: 2.39±0.10, Eccentric: 2.03±0.13; p<0.008) (Figure 15B).

The statistical analysis on *mean d'* did not showed a significant difference between Conditions (Concentric: 2.47±0.03, Eccentric: 2.53±0.03; t(34)=0.763, p=0.45) (Figure 15C).

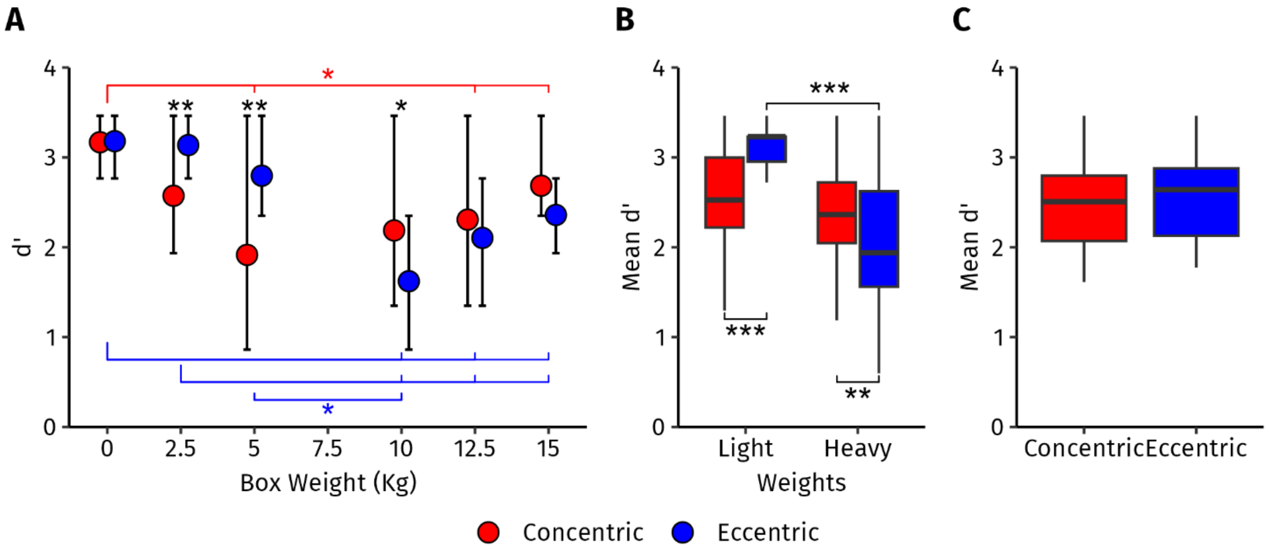

Figure 15. A) Discrimination sensitivity (d') in Concentric (red) and Eccentric (blue) condition at each weight. Circles represent median values and error bars represent interquartile interval. Black asterisks indicate significant differences between conditions (*p < 0.05, **p < 0.01). Colored brackets and asterisks indicate significant differences between weights within each condition (Concentric: red, Eccentric: blue; *p < 0.05). (B) Mean d' in Concentric and Eccentric conditions for Heavy and Light weights (**p < 0.01, ***p < 0.001). (C) Mean d' in Concentric and Eccentric conditions. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum values.

The graphical representation of the psychometric functions of the two conditions is displayed in Figure 16A.

No difference between Concentric and Eccentric was found in JND, A_{LOW}, and threshold. The result of the statistical analysis on A_{UP} showed that it was significantly higher in Concentric (0.95 [0.89, 1.00]) than in Eccentric condition (0.88 [0.80, 0.98]) (z=-2.49, p=0.021) (Figure 16B).

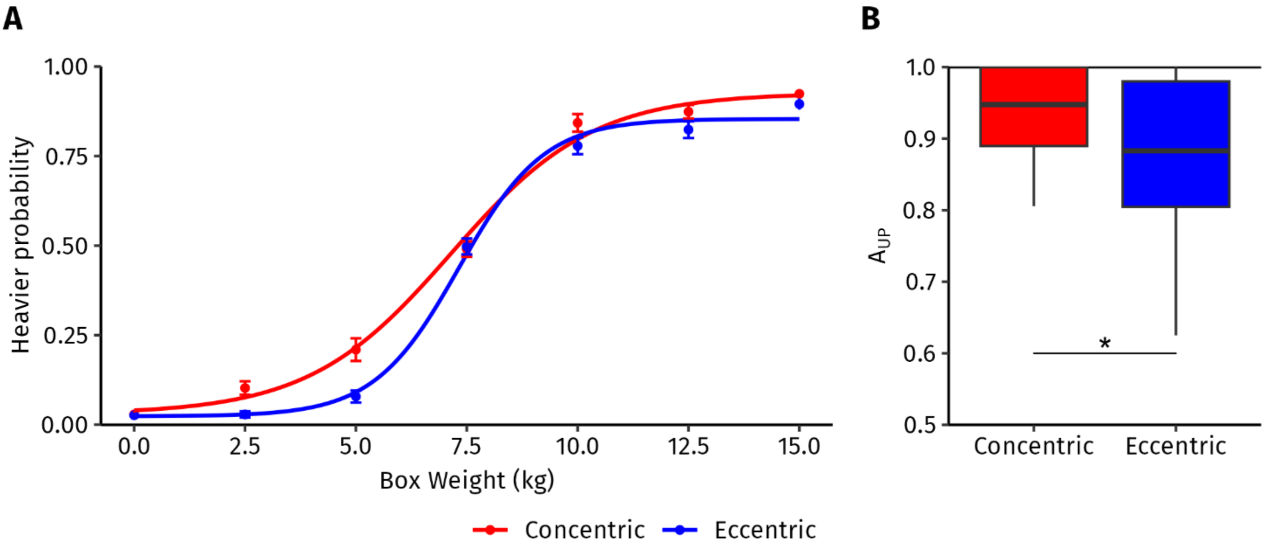

Figure 16. (A) Psychometric functions for Concentric (red) and Eccentric (blue) condition. Dots represent the proportion of Heavier responses at each load for each group, obtained from the average of the responses of all participants to each load. (B) Asymptotes (AUP) and for Concentric (red) and Eccentric (blue) condition. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. *p < 0.05.

4.4. Discussion

The aim of this study was to test if the perception of weight of an object is influenced by the kind of movement the actor performed, namely a lifting movement, involving a concentric contraction of the main muscle involved, or a lowering movement, requiring an eccentric contraction. Results showed that, in case of light boxes (when the comparison weights were below the weight of the test stimulus), discrimination sensitivity was significantly higher in Eccentric than in Concentric condition. Differently, when the comparison stimulus was 10kg, namely heavier than the test stimulus, *d'* was higher in Concentric condition, in agreement with the analysis of the recruitment curve, showing that A_{UP} was significantly higher in Concentric than in Eccentric condition. These results are confirmed by *LHmean d'*. Indeed, For Light weights *LHmean d'* was higher in Eccentric than Concentric condition, whilst this result was reversed for Heavy weights. Furthermore, within Eccentric condition, a significant lowering of discrimination sensitivity was found from all the light weights versus the heavy weights. This overall lowering was also testified by the decreases in the *LHmean d'* in Heavy than in Light condition. Within Concentric condition a significant lowering was found only among 0kg and 5kg, 12.5kg, 15kg.No difference within Concentric condition was found between

LHmean d' in Heavy than in Light condition. *Mean* d' did not significantly difference between conditions.

A number of studies have demonstrated that eccentric and concentric contractions exhibit differences in the neuromuscular features (Duchateau and Enoka, 2008) and cortical activations. Concerning the latter, electrophysiological and neuroimaging investigations reported greater activation level during eccentric than concentric contractions and motivated this phenomenon as due to the higher complexity of eccentric contractions, which thus require greater cortical resources to be accomplished (Fang et al., 2001; Kwon and Park, 2011; Yao et al., 2014). This higher brain activity pertains a multimodal-associative brain network (Kwon and Park, 2011) which is known to be involved also in weight perception (Hamilton et al., 2006; Chouinard et al., 2009). For this reason, one might speculate that the higher activation of these areas in Eccentric than in Concentric conditions results in a better weight discrimination ability.

However, this phenomenon was not generalized. Indeed, it was observed only for boxes whose weight was 2.5kg and 5kg, thus below the weight of the test stimulus. No difference between Eccentric and Concentric conditions appeared in *mean* d' values and, an inversion of this effect was even found at 10kg, where d' was higher in Concentric than Eccentric condition. This inversion was evident also when comparison stimuli that were classified in Light (0kg, 2.5kg and 5kg) and Heavy (10kg, 12.5kg and 15kg). Indeed, while for Light boxes the discrimination ability was higher in Eccentric condition, for Heavy boxes it was higher in Concentric than Eccentric condition. A possible speculation may rely in the participants' perception of the actors' effort when performing the two movements. To mask actors' effort their faces were blurred. However, information concerning the effort may derived also by looking at their movement (Alaerts et al., 2010; Shim et al., 2004) It could be possible that when looking at Heavy weights, being the force that individuals can generate during eccentric movement higher than that in concentric movements (Hortobágyi & Katch, 1990), the effort the actor manifested was lower. Thus, this would influence participants' perception in such a way heavy boxes appeared to be lighter than what actually are, decreasing LHmean d' values. To confirm this hypothesis a control experiment evaluating participant's perception of the actors' effort is needed.

In conclusion, the ability to discriminate the weight of objects moved by an actor is influenced by the kind of movement participant performed and by the amount of weights required to be judged.

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Chapter 5. The role of fatigue in load perception during an action observation

5.1. Introduction

Motor resonance or resonance behavior is the activation of the motor system during action observation and is mediated by the activation of mirror neuron system (Rizzolatti et al., 1999; Rizzolatti & Craighero, 2004). Motor resonance is determined by the observer's motor repertoire (Giacomo Rizzolatti & Craighero, 2004), and it is prevented when the observer cannot recognize the biological kinematics of the observed movement (Bisio et al., 2010, 2014). Furthermore, the possibility to map the features of the observed action into the own motor repertoire increases motor resonance, as shown by studies concerning the temporal features of movements (Avanzino et al., 2015; Lagravinese et al., 2017). Another key issue to be considered is the role played by the individual's motor abilities. Studies comparing motor resonance in athletes and novices when observing a sport gesture showed that motor resonance is greater when observing "known" than "unknown" movements, suggesting the importance of the possibility to match the observed movement kinematic into the own motor plan (Aglioti et al., 2008). Furthermore, when observing an action, the kinematics of the actor helps the observer to infer the property of the objects involved in the action, such as its weight (A. Hamilton et al., 2007; Antonia Hamilton et al., 2004), likely due to the effects the observed kinematics has on motor resonance mechanisms when object weight changes (Alaerts, Senot, et al., 2010; Alaerts, Swinnen, et al., 2010; Rens et al., 2020). Nevertheless, the sensorimotor representation of action depends also by current state of the individual and might be altered by it. For instance, it was shown that in presence of fatigability the ability to create a mental image of an action was altered (Demougeot et al., 2011). These alterations were strictly effector specific and related to action executed (Demougeot et al., 2011). This was referred both to the muscle (the agonist but not the antagonist) and to the body side (e.g. the left but not the right) involved. Further, fatigue influenced force and heaviness sensation (Jones & Hunter, 1983), changing expectation of weight involved in the action. De Lussanet and colleagues demonstrated that pain, modifying sensorimotor representation, influenced specifically weight discrimination ability (De Lussanet et al., 2012). These findings helped to strengthen the role of motor system in motion perception.

Therefore, one might hypothesize that fatigability induced by movement execution changes the observer ability to recognize the muscle effort and the weight of an object lifted during an action. To solve this issue, this study evaluated the effect of muscular fatigue on weight discrimination ability. All the protocols described hereafter were performed at the University of Burgundy, in the Centre d'Expertise de la Performance, Faculté des Sciences du Sport (UFR Staps).

5.2. Protocol 1

5.2.1. Materials and methods

Eight voluntary students were recruited (8 males, mean±SE age = 23.1 ± 0.8 years). The experiment involved a single session.

Weight discrimination ability was assessed before (Rest) and after (Fatigue) a fatiguing protocol performed using the Biodex system. The protocol consisted in performing at the isokinetic dynamometer 3 sets of 10 repetitions in eccentric condition for the elbow flexor muscles and 1 set of 30 concentric movements. Muscle fatigue was measured as a decrease in maximal strength expressed before the fatiguing protocol (PRE), at its end (POST0), and at the end of the second weight discrimination task (POST40) (Gandevia, 2001), in concentric, eccentric, and isometric conditions.

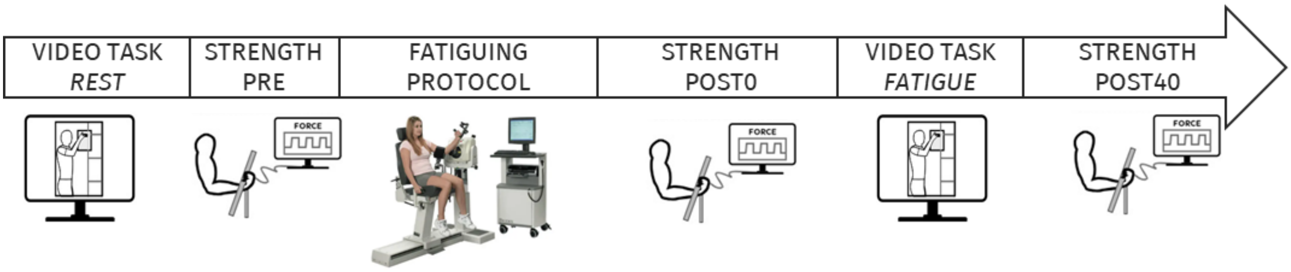

Figure 17. Session design Protocol 1

Weight Discrimination Video Task. The weight-discrimination video task was built using jsPsych 6.3.0 library and performed off-line (de Leeuw, 2015). The task was preceded by the instructions, and by a questionnaire collecting personal data (i.e., gender, age, weight, height) and physical activity level (i.e., activities performed, year of experience, weekly hours of training) data. The weight discrimination video task is represented in Figure 14.

The stimuli consisted in videos showing an actor performing an IADL; namely, the actor (either a woman or a man based on participant's gender, Figure 14B) moved a box from the chest to a shelf over the head (Concentric condition, given that the main muscle involved in the movement, i.e., the anterior deltoids, shortened in this kind of movement – based on preliminary EMG acquisitions) or bring it down from the shelf to the chest (Eccentric condition, given that the deltoids anterior lengthened). In both conditions, the box was filled with varying amounts of sheets of paper in such a way as to assume 7 different weights (0, 2.5, 5, 7.5, 10, 12.5, 15 kg). Actors were informed about the weight of the box. Videos, whose durations range from 1.3s to 3.7s, were acquired in a same day with a video-camera positioned to record the execution of the lifting movement laterally. The face of the actor was blurred to cover facial expression.

During the weight discrimination task, participants seated in front of a laptop with a 16-inch LCD screen position on a table, at a distance of about 60 cm. They were required to perform a two-interval forced-choice (2IFC) task (Duarte et al., 2018). Each trial consisted in a sequence of two videos, a reference and a comparison stimulus. After the observation of both, the observer had to indicate in which video the box was heavier. In particular, the subject had to press the left arrow key to answer "First" and right arrow key to answer "Second". The 7.5kg-video was showed every trial and represented the reference stimulus. The 0kg-, 2.5kg-, 5kg-, 7.5kg-, 10kg-, 12.5kg-, and 15kg-video were the comparisons stimuli (please notice that 7.5kg-video was used both as reference but also as comparison). In each trial, the order of appearance of the reference and the comparison stimuli was random. Each comparison video was displayed 12 times in random order for each condition, for a total number of trials corresponding to 168 (7 box weights, 12 repetitions, 2 conditions).

5.2.1.1. Fatiguing Protocol

The fatiguing protocol was inspired to that proposed by Bottas and colleagues (Bottas et al., 2010) and executed with the dominant limb. The participants performed 3 sets of 10 maximal eccentric and 1 set of 30 concentric elbow flexions with an isokinetic (constant velocity) machine (Komi et al., 2000). A warm-up consisting in 10 contractions performed at 25% of the MCV, 6 at 50% and 10 at 25% (recovery between sets is 30 s) was performed.

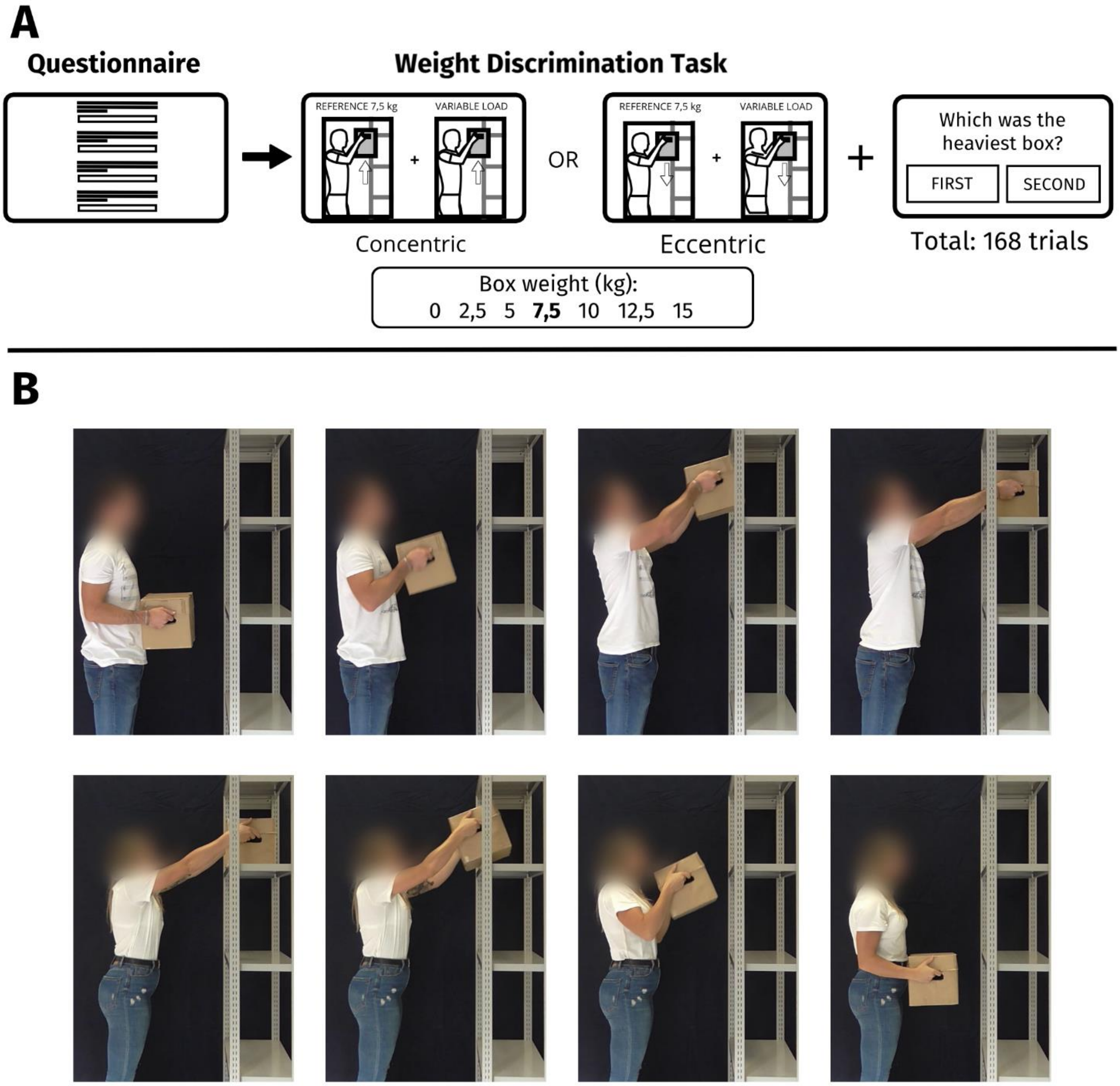

Figure 18. Experimental design. (A). Task Protocol: Each participant executed the task at computer. The participants filled a questionnaire collecting personal and physical activity related data. Then a two-interval forced-choice (2IFC) task consisted of 84 trials. Each trial contained two videos in sequence: one was the reference stimulus (box weight: 7.5 kg) and the other was one of the seven comparison stimuli (box weights: 0, 2.5, 5, 7.5, 10, 12.5, 15 kg). At the end a question asked in which video the box was heavier, and the participants could choose between “first” or “second”. (B) Frame of one video proposed participants for male and female.

The subject seated at the machine and the forearm was fixed in a supinated position. The axis of machine lever arm corresponded to the rotational axis of the right elbow joint. The force applied to the wrist for elbow flexion resisting the machine lever arm movement was measured by the Biodex system. The movement range during exercise was from 50° to 170°, wherein 180° position indicates full elbow extension. The angular velocity was set at 2 rad/s. This protocol was chosen because it has been shown to be effective in inducing fatigue and participants still exhibited significantly decreased maximum force production after 2 hours (Jildeh et al., 2019), thus allowing the following testing procedure to be performed in a fatigued state.

5.2.2. Data Analysis

The percentage of response in which the comparison stimulus was judge "Heavier" than the reference stimulus at each box weight was used to build a Psychometric function. The observers' psychometric curves were obtained by finding the best-fitting logistic functions using psyphy and quickpsy R package (Linares & López-Moliner, 2016; Yssaad-Fesselier & Knoblauch, 2006), The lower and upper asymptotes, threshold, and just noticeable difference (JND), were estimated for each psychometric function (Knoblauch & Maloney, 2012). Lower asymptote (A_{LOW}) and upper asymptote (A_{UP}) were computed according to Oh et al. (Oh et al., 2016). The lower/higher A_{LOW}/A_{UP}, the better the ability to discriminate low/high weights. The threshold corresponds to the curve point crosses 0.5 on the y-axis and indicates the point of subject equality (Kopec & Brody, 2010). JND is considered as the smallest weight that produces changing in perception and calculated as the half difference between the weights at which the psychometric function equals to 0.75 and 0.25, respectively (von Sobbe et al., 2021). A lower JND indicated a better ability to discriminate the stimuli.

5.2.3. Statistical analysis

Maximal strength assessment, A_{LOW}, A_{UP}, and JND, were considered as outcome parameters. Shapiro-Wilk test was applied to evaluate data distribution and Levene's test was used to evaluate the equality of variances. All parameters were normally distributed.

Maximal strength was evaluated by means of a repeated measure ANOVA with CONDITION (2 levels: Eccentric, Concentric) and STATE (2 levels: Rest, Fatigue) as within subject factors.

Normally distributed data are reported as mean value ± standard error (SE). Significance level was set at 0.05. Statistical analyses were performed with RStudio 4.2.2

5.2.4. Results

The ANOVA applied to evaluate the effect of fatiguing protocol on strength revealed a significant effect TIME (F(2,14)=13.5, p=0.0005, η^2=0.214) and CONDITION (F(2,14)=24.4, p<0.0001, η^2=0.229). No significant interaction TIMExCONDITION was found (F(4,28)=1.3, p<0.29, η^2=0.011). Post-Hoc analysis on TIME effect showed a significantly higher mean Maximal Strength at Pre (61.5±2.54 N) compared to Post0 (47.5±2.86 N; p<0.0001) and Post40 (49.7±3.06 N; p<0.0001), Figure 19A.

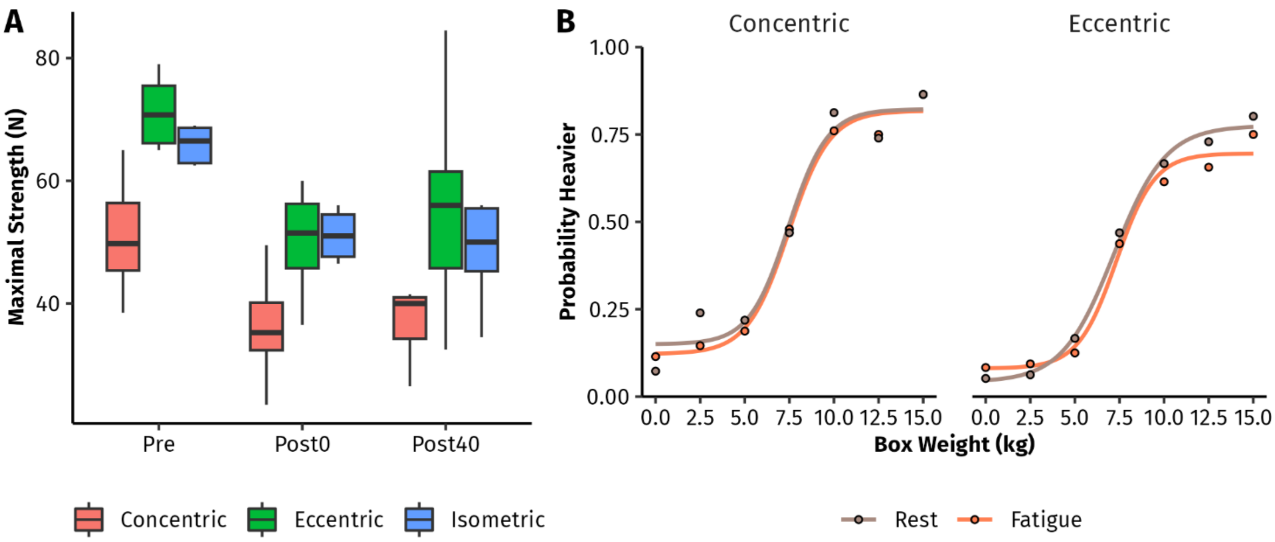

Figure 19. (A) Maximal Strength in Concentric (red), Eccentric (green) and Isometric (blue) condition at Pre, Post0 and Post40. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. (B) Psychometric functions at Rest (beaver color) and after Fatigue protocol (orange). Dots represent the proportion of Heavier responses at each load for each group, obtained from the average of the responses of all participants to each load.

The graphical representation of the psychometric functions of the two conditions (eccentric and concentric) is displayed in Figure 19B. No effect of STATE was found for all psychometric curve parameters. Only in A_{UP} a Condition effect was found (F(1,7)=8.27, p=0.024, η^2=0.197), revealing a higher value in Concentric condition (0.91±0.03) than in Eccentric condition (0.79±0.03).

	Rest		Fatigue		Statistical Analysis
	Concentric	Eccentric	Concentric	Eccentric	ANOVA Effect (p value)
A_{UP}	0.91±0.04	0.81±0.04	0.90±0.04	0.78±0.05	State: p=0.76, Condition: p=0.024*, TimexState: p=0.71
A_{LOW}	0.06±0.03	0.02±0.01	0.06±0.03	0.07±0.03	State: p=0.45, Condition: p=0.39, TimexState: p=0.31
JND	2.79±0.69 kg	3.75±0.47 kg	3.41±0.70 kg	3.63±0.55 kg	State: p=0.58, Condition: p=0.22, TimexState: p=0.35

Table 3. Psychometric curve parameters (mean±SE) and relative statistical analysis. *p<0.05

5.3. Protocol 2

5.3.1. Materials and methods

The results of Protocol 1 failed to find an effect of the fatigability on the ability to perceive the weight of the boxes. A possible reason might be that the fatiguing protocol was not specific for the body parts involved in the observed movement during the weight discrimination video task. For this reason, in Protocol 2 we proposed to another group of participants a fatiguing protocol that specifically involved the upper libs.

Eight voluntary subjects were recruited (males: 6, females: 2, mean±SE = 25.5±0.5 years). The experiment consisted in two sessions separated by a minimum of 1 week. One session evaluated the effect of fatigability in the weight discrimination (FATIGUE session), the other one evaluated the ability in weight discrimination at rest (REST session). The order of two sessions was random. During the Rest session only the weight discrimination task was performed (Figure 20).

Fatigue session. During the Fatigue Session the participants filled a questionnaire collecting personal (i.e., gender, age, weight, height) and physical activity level (i.e., activities performed, years of experience, weekly hours of training) data. The perceived

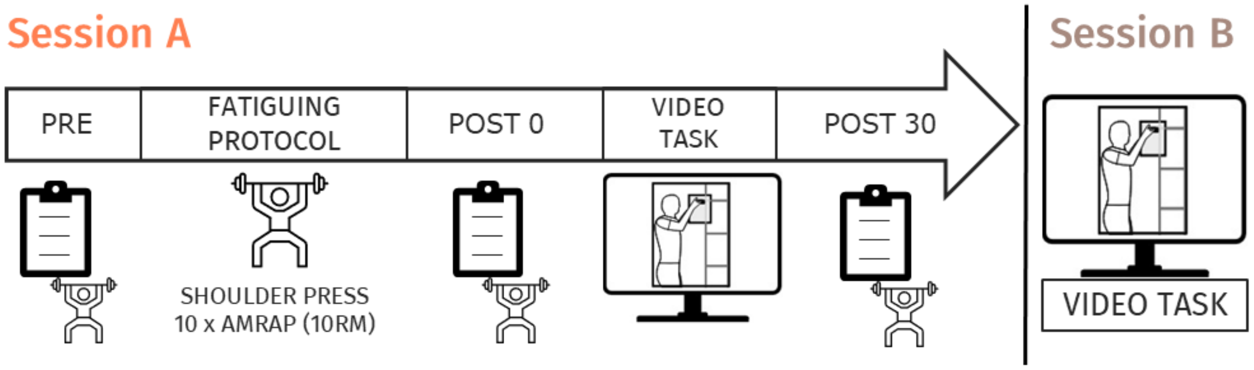

Figure 20. Protocol 2 Experimental Design

fatigue level and force were assessed immediately before (Pre), after the fatiguing protocol (Post0) and after the Weight Judgment task (Post30). In order to verify the impact of the fatiguing protocol, strength evaluation was performed during an isometric shoulder flexion pushing a bar positioned at each participant forehead level. The strength was assessed by a dynamometer (KForce Link, Kinvent). Perceived fatigue was measured with the rating of perceived fatigue (RPF) scale, a modified Borg CR-10 scale (Hewlett et al., 2011; Leung et al., 2004; Whittaker et al., 2019). The fatiguing task consisted in 10 sets of shoulder press with the load corresponding of participants' 10 Repetition Maximum (10RM), 1 minutes was given as rest between sets. After two sets of warm-up (consisting in 20 repetition of shoulder press at 50%1RM estimated load), participants performed the 10RM test to determine the maximum load that they could lift or 10 consecutive repetitions at a self-selected cadence (Da Silva et al., 2017). If the test failed (performing more or less than 10 repetitions), the load was adjusted by 2.5-5 kg. 3 minutes of rest was given between 10RM attempts. Never more than 3 attempts were necessary to find the 10RM load.

Weight discrimination video task. The video task had the same construct of which one used in the First Protocol, but only Concentric condition was given. Participants required to perform a two-interval forced-choice (2IFC) task (Duarte et al., 2018). Each trial consisted in a sequence of two videos, a reference and a comparison stimulus. After the observation of both, the observer had to indicate in which video the box was heavier. In particular, the subject had to press the left arrow key to answer "First" and right arrow key to answer "Second". The 7.5kg-video was showed every trial and represented the reference stimulus. The 0kg-, 2.5kg-, 5kg-, 7.5kg-, 10kg-, 12.5kg-, and 15kg-video were the comparisons stimuli (please notice that 7.5kg-video was used both as reference but also as comparison). In each trial, the order of appearance of the reference and the comparison stimuli was random. Each comparison video was displayed 12 times in random order for each condition, for a total number of trials corresponding to 168 (7 box weights, 12 repetitions).

5.3.2. Data Analysis

Isometric strength assessment, rating of perceived fatigue (RPF) A_{LOW}, A_{UP}, and JND were considered as outcome parameters.

Shapiro-Wilk test was applied to evaluate data distribution and Levene's test was used to evaluate the equality of variances. All parameters were normally distributed, except A_{LOW} that was not.

Isometric strength assessment and rating of perceived fatigue (RPF) Fatigue-VAS were evaluated by means of a repeated measure ANOVA with TIME (3 levels: Pre, Post0, Post30) as within subject factors. A_{UP} and JND were compared between the STATUS (Rest, Fatigue) with paired t-test, whilst A_{LOW} with Wilcoxon test.

Normally distributed data are reported as mean value ± standard error (SE), while not-normally distributed data are given as median [interquartile range, IQR]. Significance level was set at 0.05. Statistical analyses were performed with RStudio 4.2.2

5.3.3. Results

Fatigue assessment

Repeated measure ANOVA on Isometric Strength revealed a significant TIME effect ($F(2,14)=38.5$, $p<0.0001$, $\eta^2=0.105$). Post-hoc analysis showed that strength was significantly higher at Pre (33.7±2.6 kg) than Post0 (28.4 ±2.3 kg; $p=0.0005$) and Post30 (31.5±2.4; $p=0.002$), and significantly higher at Post30 than Post0 ($p=0.006$) (Figure 21A).

Repeated measure ANOVA on RPF revealed a significant TIME effect ($F(2,14)=20.2$, $p<0.0001$, $\eta^2=0.479$). Post-hoc analysis showed that RPF was significantly higher at Post0 (6.1±0.9) than Pre (1.7±0.3; $p=0.0003$) and at Post30 (4.6±0.8) than Pre ($p=0.014$) (Figure 21B).

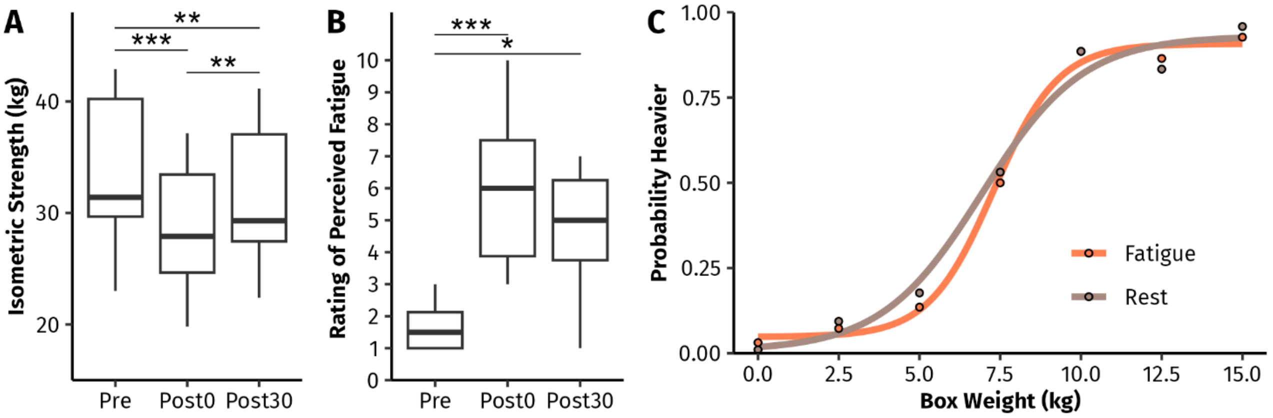

Figure 21. (A) Isometric Strength and (B) Rating of Perceived Fatigue at Pre, Post0 and Post40. The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. *p<0.05, **p<0.01, p<0.001. (C) Psychometric functions at Rest (beaver color) and after Fatigue protocol (orange). Dots represent the proportion of Heavier responses at each load for each group, obtained from the average of the responses of all participants to each load.

Psychometric function

The graphical representation of the psychometric functions is displayed in **Figure 21**C, and statistical analysis of psychometric parameters are resumed in Table 4. No differences were found in psychometric curve parameters showed no effect on weight discrimination ability, Table 4.

	Rest	Fatigue	Statistical Analysis
AUP	0.93±0.02	0.92±0.03	t(15)=0.27, p=0.80
ALOW	0.00 [0.00, 0.00]	0.00 [0.00, 0.06]	Z=0.33, p=0.742
JND	2.79±0.30 kg	1.54±0.39 kg	t(15)=0.43, p=0.68

Table 4. Psychometric curve parameters (AUP, JND: mean±SE; ALOW: median [IQR]) and relative statistical analysis to compare STATUS effect. *p<0.05

5.4. Protocol 3

Also protocol 2 failed to find an effect of the fatigability protocol on weight discrimination ability. One possible reason for these failures could be that when a subject is fatigued there is a shift in weight perception for all the amount of weights that resemble heavier than what actually are. However, in that case, a discrimination task would be not sensitive. For this reason, in Protocol 3 we applied the same fatiguing protocol as in Protocol 2, but to evaluate the ability in weight perception, we applied a weight estimation paradigm, in which subject were explicitly required to evaluate the weight of the box.

5.4.1. Materials and methods

Eight volunteers (five males and 3 females) participated in the experiment. Mean age (±se) was 26.6 ± 1.3. The experiment consisted in two sessions interleaved by a minimum of 1 week. One session evaluated the effect of fatigue in the weight judgment (Fatigue session), the other one evaluated the ability in weight judgment at rest (Rest session). The order of two sessions was random. During the Rest session only the weight judgment task was performed.

Fatigue session. During the Fatigue Session the participants filled a questionnaire collecting personal (i.e., gender, age, weight, height) and physical activity level (i.e., activities performed, years of experience, weekly hours of training) data. The perceived fatigue level and strength were assessed immediately before (Pre), after the fatiguing task (Post0) and after the Weight Judgment task (Post30). In order to verify the impact of the fatiguing protocol, strength evaluation was performed during an isometric shoulder flexion pushing a bar positioned at each participant forehead level. The force was assessed by a dynamometer (KForce Link, Kinvent). Perceived fatigue was measured with rating of perceived fatigue (RPF) scale, a modified Borg CR-10 scale (Hewlett et al., 2011; Leung et al., 2004; Whittaker et al., 2019). The fatiguing task consisted in 10 sets of shoulder press with the load corresponding of participants' 10 Repetition Maximum (10RM), 1 minutes was given as rest between sets. After two sets of warm-up (consisting in 20 repetition of shoulder press at 50%1RM estimated load), participants performed the 10RM test to determine the maximum load that they could lift or 10 consecutive repetitions at a self-selected cadence (Da Silva et al., 2017). If the test failed (performing more or less than 10 repetitions), the load was adjusted by 2.5-5 kg. 3 minutes of rest was given between 10RM attempts. Never more than 3 attempts were necessary to find the 10RM load.

Weight judgement task. The weight-discrimination video task was built using jsPsych 6.3.0 library and performed off-line (de Leeuw, 2015). The task was preceded by the instructions and a familiarization phase consisting in the execution of 6 trials. The weight judgement task was performed at computer. During the task the participants watched videos showing an actor lifting a box; namely, the actor (either a woman or a man based on participant's gender) moved a box from the chest to a shelf over the head. The box was filled with varying amounts of sheets of paper in such a way as to assume 4 different weights (0, 5, 10, 15 kg). Videos were acquired in a same day with a video-camera positioned to record the execution of the lifting movement. The face of the actor was blurred to cover facial expression. The task consisted in watching a video and then the participants answered to the question "What was the weight of the box?". Participants were required to press one of the four a buttons of the keyboard to indicate the observed weight. Each video was displayed 10 times, for a for a total number of trials corresponding to 80 (4 box weights, 2 conditions, 10 repetitions). The total duration of the experiment was about 20 minutes.

5.4.2. Data analysis

Strength and RPF were assessed to evaluate the fatigue level. Accuracy and Response Time (RT) were the outcome parameters used to evaluate the weight judgment task performance. Shapiro-Wilk test was applied to evaluate data distribution and Levene's test was used to evaluate the equality of variances. All parameters resulted normally distributed. Fatigue evaluation's parameters were compared at three times (factor Time: pre, post0, post30) with a One-way repeated measures ANOVA. A t-test was performed to compare Accuracy and RT between the 2 sessions (Rest and Fatigue). Significance level was set at 0.05. Statistical analyses were performed with RStudio 4.2.2.

5.4.3. Results

Fatigue

In the Isometric Strength assessment, there was a significant effect of Time (F(2,14) = 22.3, $p<0.0001$, $\eta^2=0.185$). The strength was significantly higher at Pre (32.3±2.5 kg) than Post0 (25.5±2.3 kg, $p=0.001$) and Post30 (26.6±2.3, $p=0.013$) (Figure 22A). In the RPF scale, there was a significant effect of Time (F(2,14) = 20.7, $p < 0.0001$, $\eta^2=0.\ 668$). The fatigue was significantly lower at Pre (1.88±0.37) than Post0 (6.81±0.68 , p=0.004) and Post30 (5.62±0.58, p=0.0005) (Figure 22B).

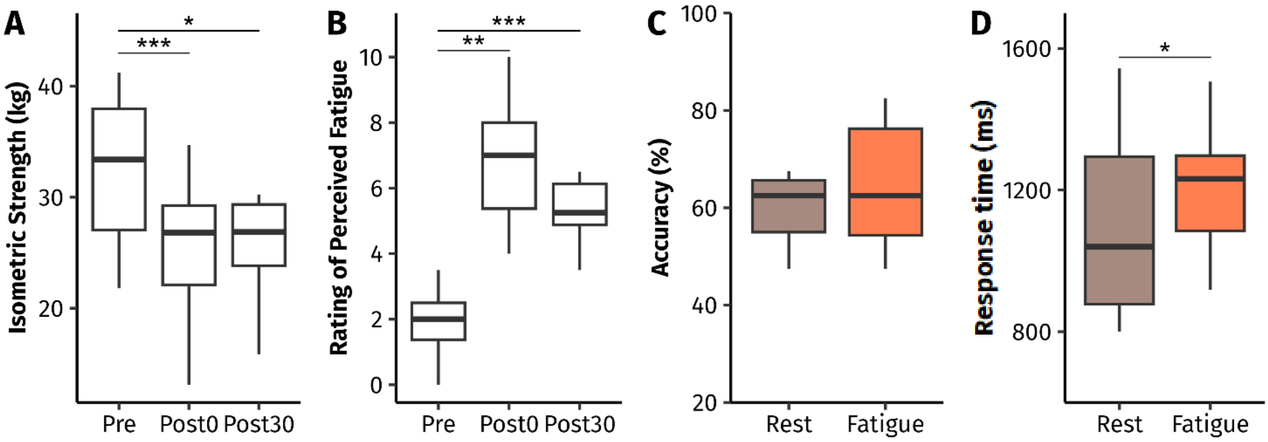

Figure 22. (A) Isometric Strength and (B) Rating of Perceived Fatigue (blue) condition at Pre, Post0 and Post40. (C) Accuracy and (D) Reaction Time at Rest (beaver color) and after Fatigue protocol (orange). The box represents the inter-quartile ranges, and the bars show the maximum and the minimum. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Weight judgement task

The result of the statistical analysis on Accuracy did not show a difference between sessions (Fatigue: 64.7±4.7%, Rest: 62.2±3.7%; t(15)=0.63, p=0.55) (Figure 22C). The analysis on Response Time revealed a significant higher value during Fatigue Session (1308±124 ms) than in Rest session (1101±101 ms), (t(15)=2.53, p=0.039; Figure 22D).

5.5. Discussion

Contrary to what expected, these results did not show an effect of fatigue on weight discrimination or evaluation. This inconsistency with the initial hypothesis is not due to the lack of fatigue experienced by the subjects, as shown by all three experimental protocols, which were effective in inducing fatigue in the participants. Fatigue exacerbated the sense of perceived exertion when lifting objects and causes an increased perception of heaviness. With sufficiently accumulated fatigue, submaximal loads are perceived as maximal (Burgess & Jones, 2009). It is possible that the fatigue protocols used here did not induced a fatiguing state so high to modify the perception of weight.

Since both motor and visual (Runeson & Frykholm, 1981) systems are involved in weight estimation, one might propose the occurrence of a compensatory mechanism operated by the visual system. Indeed, muscle fatigue leads to a change in the motor system (Demougeot et al., 2011) but not on the visual system.

The observers were more inclined to judge the lifter's effort than the actual weight lifted (Shim et al., 2004). During the observation of lifting a weight, the object weight and the effort were encoded in different areas. Mizuguchi and colleagues suggested that the sense of effort was associated with the activation of right temporoparietal junction visual areas 5/superior temporal cortices, regions related to social cognition and attention (Mizuguchi et al., 2016). Fatigue could have an effect on motor system and less or not on visual one, that could support the maintenance of the ability to evaluate object weight during moved by others at the expense of the time of such an evaluation.

In conclusion, the ability to discriminate the weight of objects moved by an actor seems to be not influenced by the observer's state of fatigue.

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Chapter 6. Conclusions and future directions

The aim of this thesis was to explore how different factors that influence the state of the observer and the nature of the observed movement determine the ability to discriminate the weight of an object during an action observation task.

The results show that motor experience in a sport involving weight lifting, i.e. powerlifting, positively influences the ability to assess weight of the barbell during the deadlift. Future studies on this matter will be devoted to understand which features of the observed movement or of the object are crucial in to accomplish this task.

This work highlights the role of age-related deterioration of the motor skills in object weight discrimination. Future studies could investigate whether training, which leads to a slowing of the decalage of physical and cognitive abilities, leads to a slowing down of perceptual abilities.

The type of movement determines a different ability in weight discrimination; concentric movements result in a worse ability to recognize light weights and a better ability to recognize higher weights than an eccentric movement. Further experiments should investigate whether this result is due to the different effort made by the actor in the two movements.

The state of fatigue appears not to influence the perception of the load of an object, this may result from the involvement of the visual system which is less likely to be affected by fatigue. Further experiments could investigate this ability in different fatigue states, e.g. it may be that mental fatigue that also affects the visual system results in a deterioration of this ability. The small number of subjects and the different protocols used represent a limitation to the investigation of this phenomenon.

Publications and abstracts

Pubblications on international journals

Albergoni A., Biggio M., Faelli E., Pesce A., Ruggeri P., Avanzino L., Bove M., Bisio A. Sensorimotor experience influences the perceptual load judgment during the observation of a sport-specific gesture. In revision on Frontiers in Sports and Active Living.

Bisio A.*, Panascì M.*, Ferrando V., **Albergoni A.**, Ruggeri P., Faelli E. Warm-up plus verbal communications administered as placebo procedure during the training session improves running performance. In revision on Psychology of Sport and Exercise.

Albergoni A., Biggio M., Faelli E., Ruggeri P., Avanzino L., Bove M., Bisio A. Aging deteriorates the ability to discriminate the weight of an object during an action observation task. In revision on Frontiers in Aging Neuroscience.

Abstracts

A. Bisio, M. Biggio, L. Pedullà, **A. Albergoni**, A. Bellosta, A. Tacchino, J. Podda, L. Avanzino, G. Brichetto, M. Bove. Motor performance of people with progressive multiple sclerosis can benefit from motor imagery training with no increase in fatigability. Annual RIMS Conference. Genova. May 4-6, 2023.

Albergoni A., Paizis C, Biggio M., Faelli E., P., Papaxanthis C, L., Bove M., Bisio A. Object weight evaluation during the observation of eccentric and concentric movements. XIII SISMES National Congress. Milano, Italy. 04-06/11/2022 (Poster presentation)

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F. Marmondi, M. Pennacchi, F. Turrini, C. Cerizza, **A. Albergoni**, L. Galli, F. Sartor, P. Cinque, M. Bonato. Activity pacing in people living with HIV: technical issues in training prescription and monitoring through the combined use of an actigraph and smartphone app. XIII SISMES National Congress. Milano, Italy. 04-06/11/2022

M. Pennacchi, F. Marmondi, F. Turrini, C. Cerrizza, **A. Albergoni**, L. Galli, F. Sartor, P. Cinque, M. Bonato. Activity pacing to monitor physical activity in people living with HIV (PLWH) using wearable devices. XIII SISMES National Congress. Milano, Italy. 04-06/11/2022

Albergoni A., Biggio M., Faelli E., Ruggeri, P., Avanzino L., Bove M., Bisio A. The role of age in the evaluation of heaviness perception. 27th Congress of the European College of Sport Science (ECSS). Sevilla, Spain. 30/08 – 02/09/2022 (Poster presentation)

A. Bisio, M. Biggio, L. Pedullà, **A. Albergoni**, A. Tacchino, L. Avanzino, G. Brichetto, M. Bove. Does action observation improve motor performance without causing fatigability in progressive forms of multiple sclerosis? RIMS Digital Conference 2021. November 26-27, 2021.

Albergoni A., Biggio M, Pesce A, Faelli E, Bove M, Ruggeri P, Bisio A. The expert's eye: powerlifters are more accurate than naïve in evaluating lifted weight in the deadlift exercise. 26th Annual Congress of the European College of Sport Science. Virtual Congress, 8-10 September 2021 (Oral presentation)

Bisio A., Panascì M., Ferrando V., **Albergoni A**., Ruggeri P., Faelli E. The effect of placebo and nocebo on running performance during high intensity interval training. 26th Annual Congress of the European College of Sport Science. Virtual Congress, 8-10 September 2021

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