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The role of colour on object sensorimotor representation

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Abstract

The human ability to interact with the environment requires a coupling between perception and action. Some of the most compelling evidence for this claim comes from the affordance studies. Affordances are object properties that refer to the possible actions can an agent can take, and they exist by virtue of a relationship between the agent action capabilities and its environment.

Through seven experiments, the current thesis aims to investigate if and how the colour of an object has a role in its sensorimotor representation, both when we see the object and when we understand its referent. Moreover, through comparison with the dangerousness of the object, the current thesis can outline, from the one hand, how our sensorimotor comprehension of the world is highly flexible and able to adapt the behaviour to the different proprieties of the object, and, from the other hand, how colour effectively modulates the motor simulation and representation of the objects, as dangerousness also does.

In the first part of the thesis, I will provide a historical background of the affordance concept, its empirical evidence and its correlates in the brain. Moreover, I will outline the neural correlates of colour processing and the main evidence of its representation as object property, and finally the correlates of involvement of sensorimotor system during language understanding.

In the second and third parts of the thesis, I will present behavioural results that aim to explore the role of colour in object sensorimotor representation and language simulation process. Results demonstrate that colour has a pragmatic role in the agent-object interaction, both when we see an object and when we understand its referent. Finally, I will discuss the possibility to extend the affordance concept to colour considering it as pragmatic property, with the theoretical implication of this point.

Riassunto

La capacità umana di interagire con l'ambiente richiede un accoppiamento tra percezione e azione. Alcune delle prove più convincenti per questa affermazione provengono dagli studi sulle affordances. Le affordances sono proprietà degli oggetti che si riferiscono alle possibili azioni che un agente può intraprendere con esso ed esistono in virtù di una relazione tra le capacità di azione dell'agente e il suo ambiente.

Attraverso sette esperimenti, la presente tesi indaga se e come il colore di un oggetto ha un ruolo nella sua rappresentazione sensomotoria, sia quando vediamo l'oggetto sia quando ne comprendiamo significato. Inoltre, attraverso il confronto con la pericolosità dell'oggetto, l'attuale tesi è in grado di delineare, da una parte, come la nostra comprensione sensomotoria del mondo è altamente flessibile e in grado di adattare il comportamento alle diverse proprietà dell'oggetto, e, d'altra parte, come il colore moduli efficacemente la simulazione motoria e la rappresentazione degli oggetti, così come fa pure la pericolosità.

Nella prima parte della tesi, verrà discusso il concetto di affordance, la sua evoluzione nel background scientifico, le sue prove empiriche e i correlati cerebrali, i correlati neurali del colore e le principali prove della sua rappresentazione, e infine, le evidenze del coinvolgimento sensomotorio durante la comprensione della lingua.

Nella seconda e terza parte della tesi, presenterà risultati comportamentali che mirano a esplorare il ruolo del colore nella rappresentazione sensomotoria dell'oggetto e nel processo di simulazione del linguaggio. I risultati mostrano che il colore ha un ruolo pragmatico nell'interazione, sia quando vediamo un oggetto sia quando ne comprendiamo il referente. Infine, sarà discussa della possibilità di estendere il concetto di affordance al colore, con le implicazioni teoriche di questo punto.

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Introduction

"Mr. I. arrived at his studio with relief, expecting that the horrible mist would be gone, that everything would be clear again. But as soon as he entered, he found his entire studio, which was hung with brilliantly coloured paintings, now utterly grey and void of colour. His canvases, the abstract colour paintings he was known for, were now greyish or black and white. His paintings-once rich with associations, feelings, meanings-now looked unfamiliar and meaningless to him. […] The "wrongness" of everything was disturbing, even disgusting, and applied to every circumstance of daily life. He found foods disgusting due to their greyish, dead appearance and had to close his eyes to eat. But this did not help very much, for the mental image of a tomato was as black as its appearance. Thus, unable to rectify even the inner image, the idea, of various foods, he turned increasingly to black and white foods-to black olives and white rice, black coffee and yogurt. These at least appeared relatively normal, whereas most foods, normally coloured, now appeared horribly abnormal. His own brown dog looked so strange to him now that he even considered getting a Dalmatian."

Oliver Sacks, An Anthropologist on Mars. The case of colour-blind painter (1995)

In these passages, Oliver Sacks described the all-encompassing experience of our colour vision through the loss of it. In the novel, the author continues to describe the drama of the painter that became colour blinded after a car incident, underlining the "wrongness" of the painter daily life. Nevertheless, it is not necessary to live dramatic experiences to consider the pervasiveness of colour in everyday interaction with the world. For example, image to have in front you a basket full of strawberries. Half of them are green and the other half looks a good red colour. You decide to grasp and eat one of those strawberries, you almost surely will pick up the one of the red strawberries. In this example we are taking into account two mainly features in order to select and grasp: the colour and the shape. Likewise, if we imagine a strawberry, the imagined strawberry has a distinctive shape and also a distinctive colour, and this happens also if we verbally describe a strawberry. Moreover, many objects in the world have a distinctive colour, and the interaction with them take into account our experience of what we "believe" is the correct or normal or canonical colour of the object. In other words, our expectation about what is the right colour for an object influences if and how we interact with it. Thus, in this way, colour could encourage us to interact or not interact with the object.

As highlighted by the excerpt, colour is a fundamental aspect of our perceptual experience of the external world and it has always been interested people, as can be seen in the ample body of research conducted over the past century in physics, physiology, and psychology of colour, but also in arts, economies and so on. For example, numerous researches have shown that colour is one of the basic building blocks of visual perception. Colour affects how we group and segregate visual information to generate meaningful objects in the world (Fine, MacLeod, & Boynton, 2002; Schulz & Sanocki, 2003). Surprisingly, although a large amount of studies and interest have been done to determine the role of colour in human life, the question of if and how colour affects the interaction with objects did not obtained much attention.

In the last two decades, Embodied Cognition (EC) approaches argued that the knowledge about the object is grounded in the body in interaction with the world (Wilson, 2002), and objects are represented as patterns of potential actions, rather than in terms of their solely perceptual characteristics (Barsalou, 2008). Similarly, in 1969, Gibson proposed that the world is perceived not only in terms of objects shapes and their physical properties but also in terms of possibilities for action. In other words, we not only perceive the physical properties of an object, but mainly what we can do with it, according to internal motivation and acting possibilities. These action possibilities, emerging from the coupling between perception and action, were called affordances. For the author, affordances are:

“The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or for ill.” (Gibson, 1969)

To date, there has been a proliferation of proposals and revisions in the literature about the affordance concept, from which has been emerged the need to expand the definition of affordance, taking into account both what happens in the brain and the complexity of factors in daily interaction. The affordance concept has been embedded within a broader conceptual framework of EC, gaining to evidence to sensorimotor understanding of the world. However, if from one hand we witness, for example, a multiplication of studies that have shown that the presence of more than one object in the visual scene active multiple motor representations and these are modulated by the congruence between the objects, on the other hand we have a shortage of studies that documented how the different perceptual aspects of a single object are integrated so as to maximize the possibilities of interaction with it. Precisely in relation to this point, one of the characteristics (often and perhaps improperly) neglected is the colour of the objects. Colour, in the field of affordance, has often been used as a "control condition", with the assumption that this does not contribute (or at least not significantly) to the sensorimotor representation of the object.

Bompas and O'Regan (2006a, 2006b) so far approached the colour perception as sensorimotor interplay between sensors (e.g. cones) and the environment through active exploration of it. More precisely, colour perception could emerge by the transformations in cones excitation when eyes move to explore the ambient or, by a learned coupling between sensation and action. In the sensorimotor approach to colour perception, action influences colour perception but how colour could influence daily action has not been addressed.

The current thesis will try to shed light on the role of colour in sensorimotor representation of the objects, demonstrating that it has a pragmatic role in the interaction, both when we see an object and when we understand its referent. In the first part of the thesis, I will discuss the affordance concept, its evolution in the scientific background, its empirical evidence and the brain correlates, the neural correlates of colour and the main evidence of its representation, and finally the correlates of sensorimotor involvement during language understanding. In the second and third parts of the thesis, I will present behavioural results that aims to explore the role of colour in object sensorimotor representation and language simulation. Finally, I will discuss the possibility to extend the affordance concept to colour considering it as pragmatic property, with the theoretical implication of this issue.

Chapter One
The Affordance

1.1 Historical background of affordance concept

Over the last three decades, a growing number of researches have investigated the concept of affordance to understand the relationship between action and perception. Affordance term was coined by Gibson (1986; 1979), and it refers to possibilities for action provided to an animal by the environment. The origin of this concept is linked to Gibson's theory (1966; 1979) of "direct perception". Direct perception is defined as adequacy of the information collected by our sensory systems without the need for higher-level cognitive processes mediation between our sensory experience and our perception. In similar way, also early perception researchers speculated that vision and action systems evolved together to enable successful interactions with the environment (e.g. Koffka, 1935), capturing the idea that we can perceive the functional and relational aspects of an object directly without an a-priori knowledge or categorization. For example, in Principles of Gestalt Psychology Koffka (1935) wrote: *"Each thing says what it is […] a fruit says eat me"*.

According to Gibson, direct perception of object affordance results from the simultaneous presence of that object in the environment and any animal that has the capabilities to perceive and use it. In *Ecological approach to visual perception* (Gibson, 1986; 1979), the author provided many examples of this concept: a chair affords sitting, a button affords pushing, the floor affords walking across, and so on. Interestingly, also colour is used as example:

"The different substances of the environment have different affordances for nutrition and for manufacture […] Solid substances have characteristics surfaces. Depending on the animal species, some afford nutrition and some do not. Fruits and berries, for instance, have more food values when they are ripe, and this specified by the colour of the surface."

According to the author, affordances exist by virtue of a relationship between the action capabilities of an agent and its environment. Object colour seems to be a perfect field of investigation to deeply explore and understand the relation between action, perception and cognition.

The concept of affordance has been rapidly gaining popularity in neuroscientific literature in the last two decades, but it has been assuming slightly different definitions in order to shed light on the circular relation between action, perception and cognition. Recently, some authors have considered affordances as the product of the conjunction of visual and motor experiences in the brain (Ellis & Tucker, 2000; Tucker & Ellis, 1998). This change of perspective has produced impressive behavioural and neural results in the last years, providing an empirical methodology, or a sort of empirical signature, to investigate the ample Gibson's concept of affordance. Ellis and Tucker (1998, 2000) showed that properties of the object, such as its shape, size, and orientation, drive the activation of specific components of reaching and grasping actions. In other words, object features (e.g., size, orientation) facilitate the participant's responses when these features are compatible with the action needed to handle it (e.g., an index-thump grip for a coin or a whole hand grip for an apple) in comparison to the incompatible cases. The authors speculated that these features could evoke a particular type of hand shape during the sight of an object. The authors called these *micro-affordances*, to distinguish them from the more general concept affordances. The micro-affordance proposal allows us to keep the direct link between perception and action, but also to explore the neural representation of the dynamics between the environment and the organisms. Bub, Masson, and Cree (2010; 2008) found that different purposes of use evoked different grasping gestures, extending the micro-affordance perspective. They documented two types of manipulation knowledge: one functional and another one volumetric (for instance, using a hammer to nail or using a hammer to move it). This approach implies that the micro-affordances are flexible, continuously modified and updated in function of novel experiences (Borghi & Riggio, 2015).

More recently, it has been proposed that affordances can be either stable or variable (Borghi & Riggio, 2009, 2015), when we taking into account specific action components. According to these authors, stable affordances derive from perception-action patterns stored in memory, resulting from consolidated and constant (or relatively constant) experiences across different contexts of hand-object interaction. Typical stable affordances are the size, the shape, or the canonical orientation of an object. A subset of stable affordances are the canonical affordances. The canonical affordances are characterized by a higher degree of variability and contextual dependence in comparison to the purely stable affordances. Canonical affordances derive from properties that vary in relation the interaction with us, such as orientation, but that can become more stable across various occurrences. For instance, we might consider cherries as having a typical orientation: they are rarely grasped with the petiole on the below side, since we typically pick them up from trees, from containers or table, and in all these cases they have the petiole on the upper side. Canonical affordances are more related to the actions and the intention of use that we more frequently perform with an object. In contrast, variable affordances concern aspects that derive from temporary object characteristics (e.g., the spatial location of an object) and need constant and online updating of information in order to define the current state of the object. Besides, variable affordances are contingently associated with the actions we are about to execute. Broadly speaking, the same object, for example a cherry, can be in a tree, on a basket, on a table and so on, and its petiole can be downright or upright, or but less or more tilted. When we decide to grasp, we may need to online adapt our reach-to-grasp movement to the current location of the object (Borghi & Riggio, 2015). Given the variable nature of this information, it does not make sense to store it in memory. This is particularly useful in explaining what happens during language comprehension.

It has been demonstrated that specific motor programs are evoked not only by visual objects but also when reading nouns of graspable objects (Marino et al., 2014; Tucker & Ellis, 2004). Hence, if the object defined by the noun requires either a precision or a power grasp (due to the size of the object), manual responses are facilitated when the response grasp is compatible with the grasp evoked by the object (Borghi & Riggio, 2009). Conversely, when a task involves temporary object features during language comprehension, these do not influence the performance. For example, Ferri and colleagues (2011), in experiment 2, showed that the object location in 3D space (reachable vs. non-reachable) did not influence the response of participants when the task required to indicate, performing either a power or precision grip, whether the object picture corresponded to the object defined by the noun previously presented. In light of these findings, it seems that language acts as a sort of filter, encoding only some kinds of affordances. In particular, it seems that stable affordances are primarily processed during the comprehension of language, and conversely variable affordances play a key role with visual objects (Borghi & Riggio, 2015).

As previously introduced, all these aspects, both from visual and language, can be placed in a broader theoretical framework of EC (Barsalou, 2008) in which cognitive processes are based on action and oriented towards action. Therefore, objects (both "semantic" and "visual" objects) are represented as patterns of potential actions, rather than in terms of their only perceptual characteristics. There are some substantial differences between visual objects and semantic representation of objects. When we observe an action or look at an object, all object features are fully specified. For example, when we observe an individual performing a reaching-to-grasp movement directed towards an object, we see not only how the grasping hand moves or the context in which the movement is performed, but also the location of the object as well as its size and orientation. This enables us to activate a detailed motor program in which the parameters of the component of reaching (e.g., hand velocity and movement amplitude) and the parameters of the grasping component (e.g., hand posture and orientation) are entirely specified. In contrast, when we understand a sentence describing a reaching-to-grasp movement directed towards an object such as for example 'James grasps the cup' it is not clear how the subject's hand moves, the context in which the action is performed, the object position and so on. Nevertheless, an activation of a motor program still occurs. The embodied approach upholds that language re-recruits mechanisms and processes of perception and motor systems, without exactly reproducing them (Anderson, 2010; Gallese, 2008; Taylor & Zwaan, 2008). The recruitment would take place via mental simulation processes of experiential traces in the brain (Barsalou, 2008; Glenberg & Kaschak, 2002; Martin, 2016; Richter, Zwaan, & Hoever, 2009). These experiential traces are shaped through one's interactions with objects, or with any kind of event in general, together with the words used to denote the event. Afterwards, when reading or hearing a word without its referent, the corresponding experiential trace get reactivated, enabling the comprehension of the word itself (Lachmair, de la Vega, & Kaup, 2016)

In next paragraphs I will outline the main findings concerning object visual features as empirical signature of affordance and empirical findings of affordance in EC field of language comprehension.

1.2 Object size and orientation: the empirical signature of affordance

As previously introduced, many studies support the idea that stimuli with action significance would provoke the automatic predisposition to relevant actions. It seems that two object characteristics are especially salient to evoke the motor representation: size and orientation. The first one is a stable affordance parameter. The second one, the orientation, is a variable affordance but in the case of tools, this characteristic could become a canonical affordance.

1.2.1 Object size

As shown by Ellis and Tucker (2000), the mere observation of object properties influences the response even when these properties are irrelevant to the task. In the typical paradigm, participants had to judge if a picture refers to a natural or an artificial object (e.g., cherry or tennis ball) performing a power or a precision grip.

Participants give precision grip faster than power one when viewing small objects and vice versa for large objects. Since small objects are usually grasped with a precision grip and large ones with a power grip, this result shows an action compatibility effect (of about 20 ms). Vainio and colleagues (2008) showed, in experiment 3, that the motor activation driven by observed actions can affect the automatic generation of a grasp motor program (driven by the visual object). They investigated whether the emergence of the compatibility effect driven by the object size would be affected by the congruence/incongruence between the viewed grasp (as prime) and the object size. Taylor and Zwaan (2010) in three experiments, demonstrate that the quality of the grasp can be affected by the size of a visual stimulus (Experiment 1) only when the stimulus appears to be graspable (Experiment 2). Moreover, the results showed that the object categorization (spheres or planets) influences the affordance effect. The size effect was also found in visual mental imagery of objects (Derbyshire, Ellis, & Tucker, 2006). A fMRI study (Grèzes, Tucker, Armony, Ellis, & Passingham, 2003) found not only compatibility effects between type of grasp and size of the object using behavioural measures, but also that cerebral activations covaried with the action compatibility effects in parietal, dorsal premotor and inferior frontal cortex. They suggested that the activation, within this network, reflects the conflict between the action afforded by the picture and the action specified by the task. Girardi and colleagues (2010) investigated the effects of object affordance in reach-to-grasp actions. They used kinematics parameters to determinate the compatibility effect. Results showed that the size of the depicted object affected the grip aperture and the reach-onset times (i.e. reaction times) of compatible and incompatible actions.

In two studies, which used modified Ellis and Tucker' paradigm, Makris, Hadar and Yarrow (2011, 2013) confirmed that visual objects potentiate congruent motor programs even in cases where there is no intention to execute the motor command (2011). Participants, differently from previous studies, had to detect the stimuli in the parafoveal region, thus, processing their physical characteristics with lower resolution. Nevertheless, stimuli could still excite the motor system eliciting programs for relevant actions (2013).

These behavioural data can be, also, discussed in the light of imaging studies and direct single cell recording. Single cell recording data on monkey brain (Raos, Umiltá, Gallese, & Fogassi, 2006) showed that the visuomotor transformation related to object grasping occur in the AIP (anterior intraparietal area) - F5 circuit. This circuit is involved in the selection of the appropriate motor schemas for the potential actions. The F5 neurons (canonical neurons) are predominantly motor, and they are differently activated according to the shape of the hand during the motor act (Rizzolatti et al., 1988; Rizzolatti & Luppino, 2001). Canonical neurons code three different kinds of grip: precision grip, whole hand (power grip) and finger prehension. Conversely, the AIP neurons are more visual and likely to render visual affordances (a pragmatic representation) available to the motor system. These neurons coded three-dimensional objects in visual terms (Murata, Gallese, Luppino, Kaseda, & Sakata, 2000) independently from their position in the space (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995) and only when the objects are in the peripersonal space (Bonini, Maranesi, Livi, Fogassi, & Rizzolatti, 2014). Further evidence comes from two experiments of inactivation of the AIP neurons (Gallese, Murata, Kaseda, Niki, & Sakata, 1994) and F5 neurons (Fogassi et al., 2001). The inactivation produces a mismatch between the size and shape of the object and the correct aperture and shape of the hand. Consistent with these findings, fMRI and PET studies in humans showed a selective activation for pictures of tools in the ventral premotor cortex (Chao & Martin, 1999; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Knight, Richard Staines, Swick, & Chao, 1999). This activation seems specifically for manipulable objects but not for not manipulable ones (Kellenbach, Brett, & Patterson, 2003). These findings seem to suggest activation of motor components in response to the structure of objects, corroborating the idea that the processing of object size is in function of the action.

1.2.2 Object orientation

Evidence shows that location and orientation of the whole object, or of possible graspable parts of it (typically the handle) activate actions. In this paragraph with the term orientation, we will refer to the orientation of the graspable parts of an object. In this case, there are many examples showing better performance when the object graspable part and the response spatially correspond. This effect has been explained according to two different kinds of compatibility: spatial stimulus-response compatibility (SRC) and action compatibility. The first refers to the well-known Simon effect (Simon, 1969) that consists of faster responses when the stimulus and response locations correspond than when they do not (Proctor & Reeve, 1990). Typically, in the Simon task, a geometric shape is laterally presented, to the right or the left of fixation, and participants have to respond to a non-spatial property of the stimulus, irrespective to its location. Notably, this effect also occurs when participants have to respond to the colour of the stimulus. The SRC effect is generally explained by dual-process model in which goal-oriented response activation competes with an environmentally, or exogenously response that corresponds to features of the target stimulus (e.g., Kornblum, Hasbroucq, & Osman, 1990). The action compatibility refers to faster responses when the object handle is on the same side of the response hand, in comparison to when they are on opposite sides. In this case, the object is presented centrally, but the handle is to the right or to the left of the fixation and therefore an SRC explanation is possible. The action compatibility effect is an indication that the graspable part of the object elicits motor programs of the hand suitable to reach and grasp it (Ellis & Tucker, 1998). It is important to emphasize that the handle orientation is irrelevant for the task itself that usually consists in judgments of the vertical orientation of the object or a priming task. Several studies were performed to distinguish between the two compatibility effects when handled objects are presented (Ambrosecchia, Marino, Gawryszewski, & Riggio, 2015; Buccino et al., 2005; Iani, Baroni, Pellicano, & Nicoletti, 2011; Riggio et al., 2008; Symes, Ellis, & Tucker, 2005), but we will limit ourselves to treat studies that have a significance for the relation between action and colour.

In a vertical orientation judgment task, participants are instructed to make push-button responses with the left or right hand, depending on whether the object is upright or inverted. The stimuli used for this type of task are often tools. In experiment 1 and 2 of their study, Tucker and Ellis (1998) found an action compatibility effect of about 10 ms. Similar results were found by Derbyshire et al. (2006) and Symes et al. (2005). Pellicano and colleagues (2010) found similar results with a light torch as a stimulus. In this case, the authors used a more symmetrical stimulus with respect to a handled object to explore compatibility effects partially excluding attentional or Simon-like interpretations. A partial replication of this study (Song, Chen, & Proctor, 2014) found similar results using the same stimuli of Pellicano et al.' study. Song et al. manipulated the pictures according to the results of the survey. In the survey, the authors asked the participants which elements of the picture they used to determinate the orientation of the torch. The authors eliminated all cues (handle, switch and flashlight) from the image that could indicate the orientation of the torch and modified an internal pattern of the picture (they removed the three strips farthest from the torch head). In the final experiment, the authors found an SRC effect. Consequently, participants responded faster to the torch head in comparison to the barrel, by which one would typically grasp a torch without an explicit handle. The authors discussed their results as evidence that spatial properties of visual features and responses are crucial to the compatibility effects that, therefore, are not related to affordances or an action compatibility effect (Cho & Proctor, 2013). Similarly, in a series of papers, Cho and Proctor (2010, 2011) and Song, Chen, and Proctor (2014) proposed that the action compatibility can be more similar to Simon-like compatibility effect between left-right responses and the side of the graspable part of the object (i.e. the handle). They found that reaction times are often faster when the location of the handle, though irrelevant to the task, is aligned to the position of the response key than when it does not. In other words, this effect might be nothing else than a spatial SRC effect, based on an abstract spatial coding (see also Anderson, Yamagishi, & Karavia, 2002). To fill the gap between Tucker and Ellis' results and Cho and Proctor' results, Pappas (2014) suggested that the depth information could be critical to affordance orientation effects. As Pappas showed, the studies that reduced the depth information and internal details (e.g., Cho & Proctor, 2010, 2011, 2013; Anderson et al., 2002; Pappas, 2014, experiment 1 and 4), did not elicit affordance compatibility effects. In contrast, a robust SRC effect was found in the case of missing depth information.

Evidence that affordance orientation effect occurred in the presence of depth cue comes from Symes and colleagues' study (2005). They found a Simon-like effect when they used a rectangle in a two-dimensional space. In contrast, they found an affordance orientation effect when they used a cylinder as stimulus in a 3D space. Moreover, the orientation effect increased when the cylinder was orientated in depth on the 3D space rather than just frontally, such that its head edge appears to tend outwards in space. Furthermore, the studies of Costantini and colleagues underline the importance of space and consequently of the information about the depth of the object (Ambrosini & Costantini, 2013; Costantini, Ambrosini, Scorolli, & Borghi, 2011; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; De Stefani et al., 2014). All these findings seem to suggest that a lack of this kind of cue makes the motor system unable to determinate a correct motor program to interact with the object. Priming studies (Bub, Masson, & Kumar, 2018; Masson, Bub, & Breuer, 2011; Phillips & Ward, 2002) showed robust affordance effects, induced by the orientation of the prime stimulus, and differently for the right and left hand (Janyan & Slavcheva, 2012). Moreover, the action compatibility was obtained in a temporal order judgment task (Ariga, Yamada, & Yamani, 2016). Results revealed that right-handed participants perceived the cup with the handle oriented to right earlier as compared to the cup with the handle oriented to the left. Moreover, the effect disappeared when the cup was presented upside down

The debate around the explanatory validity of the motor and spatial accounts is still open and fuelled by opposite findings of recent works manipulating different variables (for a recent review and meta-analysis see Azaad, Laham, & Shields, 2019), such as the nature of stimuli (silhouette-like pictures vs photographs of real objects: Pappas, 2014; Proctor, Lien, & Thompson, 2017); the type of task (unimanual vs bimanual discrimination: Tucker & Ellis, 1998; Cho & Proctor 2010) or the type of response (key-presses vs directed actions Iani et al., 2011; Pavese & Buxbaum, 2002). In actual fact, tasks in which a real interaction between the object and the effector is expected provide evidence of motor activation specifically linked to the handle. For instance, Rounis, van Polanen & Davane (2018), using kinematic measures, have observed effects of the cup handle on grasp movement execution, even though participants were not explicitly instructed to grasp the handle itself.

Concerning imaging evidence, in an interesting fMRI study (Rice, Valyear, Goodale, Milner, & Culham, 2007), graspable or non-graspable objects were shown orientated to either the left or to the right. After a brief mask stimulus, the same object was shown again. The object could be oriented in the same direction of the first stimulus or in different direction (first stimulus with left orientation -> second stimulus with right orientation, and vice versa). Participants had to discriminate if the two following objects were in the same orientation or not. Results revealed a selective differential activation of the right lateral occipital-parietal junction for orientation, only in the case of graspable objects. Similarly to Pappas (2014), these studies emphasized the influence of rich visual information to trigger motor knowledge. Imaging studies showed that viewing and naming pictures of objects activate the left ventral premotor cortex (Chao & Martin, 1999). Creem-Regehr and Lee (2005) found differential activation in the fronto-parietal-temporal network for visual tools in comparison to graspable shapes. It seems that, in the brain, tools are a particular kind of targets, because they have a visual arrangement that affords action and also a distinct functional identity. The authors suggested that the functional status of graspable objects influences the extent of motor representations associated with them. As presented above, Borghi and Riggio (2009, 2015) highlighted that affordances can be stable or variable. As to their locus of neural representation, the authors proposed that stable and variable affordance are represented differentially in dorsal pathway. In particular, stable affordances are represented more ventrally compared to variable ones. The subdivision of the dorsal stream into a dorso-dorsal and a dorso-ventral system (Pisella, Binkofski, Lasek, & Rossetti, 2006; Rizzolatti & Matelli, 2003) seems to reflect how these two kinds of affordances are represented in the brain. A recent meta-analysis of fMRI data on object interaction targeting (Sakreida et al., 2016) seems to support the idea of these two separated, but some extent overlapping, functional pathways correlate to the brain representation of stable and variable affordances, giving support to Borghi and Riggio' proposal (2009, 2015). The functional characteristics of ventro-dorsal and dorso-dorsal streams will be discussed in the next paragraph.

1.3 Two (or three) routes to action

Traditionally, research has quite understandably focused on the role of visual perception in action planning and execution, as vision provides motor areas with a primary source of perceptual feedback to guide actions. The assumption that the visual system should generate an internal representation of the perceived objects is based on the traditional approach to perception. Each characteristic is analysed separately, and the percept would take shape in a “conscious area” of the brain. Two functionally and anatomically distinct streams seem to reflect two distinct modules that use the visual information for different goals. According to this view, ventral and dorsal streams play the role of generating the percept, and over the last decade, the dichotomy between the two ways of higher visual processing (Goodale & Milner, 1992; Milner & Goodale, 2008) has gained support.

These two systems were first identified in the monkey, as two functionally and anatomically distinct circuits, originating from striate cortex. The dorsal stream is meant to subserve spatial vision and action, whereas the ventral stream is more implicated in the analysis of visual features (Haxby et al., 1991; Mishkin & Ungerleider, 1982). The two streams are involved in two quite different functions that are identification and recognition (i.e. vision-for-perception) and guided actions (i.e. vision-for-action). Accordingly, object properties (as orientation, size, and shape) can be used to represent both the 3D structure of an object and to feed motor system parameters to code online the trajectory of the arm. In the first case, the purpose is to match the object to a structural representation stored in memory (Biederman, 1987), to recognize it. In the second case, these object properties can allow, within different spatial frameworks (Bruno, 2001), to correct the arm trajectory and the shape of the hand while approaching an object with the purpose of grasping it. This proposal is often referred to as the “two visual system hypotheses” (TVSH).

The dorsal pathway is an occipital-parietal network that generated from the primary visual cortex (V1) and extended to the posterior parietal cortex (PPC). The dorsal pathway regions are involved in the visually-guided action, somatosensation, spatial audition, space-related functions (working memory, navigation, spatial attention). Thus, the visual input is more related to monitoring online relations between action goals and effectors. What the object represents in the vision-for-action system is linked to the current state of relevant effectors (Bruno & Battaglini, 2008). This representation is functional to generate an accurate map of the relative position and spatio-temporal relations (dynamic and arbitrary) between object and effector.

Conversely, ventral pathway allowed the object recognition, and it privileges context-sensitivity and allocentric representation. These representations remain stable across spatial and temporal changes. This pathway is an occipitotemporal network that bridges the V1 to the inferior temporal cortex (IT). The ventral pathway is also connected with several subcortical structures involved in memory, learning, emotion, reward and value attribution. All these structures participate in forming accurate object representations based on constant aspects of visual information. The constant information is derived from features or perceptual characteristics (e.g., shape, colour, size, brightness) already available in cortical early stage of vision processed directly from the retina. Kravitz and colleagues (2014) underlined that the ventral stream processes the object *quality*.

More recently, Rizzolatti and Matelli (Rizzolatti & Matelli, 2003) suggested a further subdivision of dorsal pathway in the dorso-dorsal stream and the dorso-ventral stream, by anatomical data and a reconsideration of functional and clinical data. Dorso-dorsal stream is involved in online action control, while the ventro-dorsal stream participates in sensorimotor transformation, space perception and action recognition (Binkofski & Buxbaum, 2013; Gallese, 2007). In this subdivision, the dorso-dorsal stream is most direct and immediate pathway for visual information processing and thus supports an online mode of fast visuo-motor transformation, like an “automatic pilot” (Rossetti et al., 2005)

Focusing on ventro-dorsal stream, it is constituted by areas involved in visuo-motor transformation, such as VIP and AIP (Murata et al., 2000; Sakata, Taira, Murata, & Mine, 1995). Specifically, it extends from middle temporal area (MT) to inferior parietal lobule and intraparietal sulcus. Moreover, it projects to ventral premotor cortex areas, such as F4 and F5 (including AIP-F5 circuit involved in visuo-motor transformation for grasping, and VIP-F4 circuit involved in coding reaching space, see Rizzolatti, Luppino, & Matelli, 1998; Luppino, Murata, Govoni, & Matelli, 1999).

The ventro-dorsal stream appears the best candidates to processing sensorimotor information based upon long-term object use representations. The ventro-dorsal stream participates in more "cognitive'' aspects of action (e.g. typical use of the objects) requiring knowledge of skilled object interaction. This stream is strongly interconnected both with the ventral stream and the dorso-dorsal stream (Nelissen & Vanduffel, 2011; Pisella et al., 2006; Zhong & Rockland, 2003).

The functional characteristics of ventro-dorsal and dorso-dorsal streams parallels with the proposal of stable and variable affordances (Borghi & Riggio, 2009; 2015). Some stable parameters are needed to program actions, in particular if we have to program them offline, without having an object or an entity in front of us. The functional aspects and the connections with long-term memory areas of the ventro-dorsal stream are in agreement with the stable affordance definition. Conversely, the characteristics of the dorso-dorsal stream reflect the information needed to elaborate variable affordances.

1.4 Colour as object quality

Colour is one of the most studied object qualities (Kravitz et al., 2014). The physiology of colour processing and the central role of ventral areas involved in colour perception are well documented. The signal originates in cones, proceeding to the striate cortex through geniculate neurons of the thalamus. Traditionally, visual area V4, part of the ventral pathway, was considered to be the principal network in colour perception (Van Essen & Zeki, 1978; Zeki, 1983c, 1983a, 1983b; Zeki & Marini, 1998), particularly for processing colour associated to a specific shape. However, further studies (Desimone & Schein, 1987; Schein & Desimone, 1990) have shown that the colour selectivity of V4 cells appears to be similar to that of neurons in earlier areas, and that the proportion of colour-selective cells is believed to be high in the inferior temporal (IT) cortex (Gross, Rocha-Miranda, & Bender, 1972; Komatsu & Ideura, 1993; Komatsu, Ideura, Kaji, & Yamane, 1992). Activity in the IT cortex may reflect the elaboration of perceptual colour categories (Komatsu & Ideura, 1993). Gegenfurtner and Kiper (2003), on the basis of neuropsychological evidence (Clarke, Walsh, Schoppig, Assal, & Cowey, 1998; Rüttiger et al., 1999; Schoppig et al., 1999), posited that colour perception resulted from concomitant neuronal activity belonging to different cortical areas, and this simultaneously diffused activation seems to be the basis of our conscious experience of colour. If the role of the ventral areas in colour processing is well accepted, it follows that also dorsal areas receive input from cones (Almeida, Fintzi, & Mahon, 2014; Gegenfurtner, Kiper, & Levitt, 1997).

According to the embodied view of cognition, information about the properties of an object, such as what it looks like or how it is used, is stored in our perceptual, action, and affective systems. This means that object-associated properties (i.e. object qualities) are located within, and overlap with, the areas involved in the analysis of these properties (Kiefer & Pulvermüller, 2012; Martin, 2016; Thompson-Schill, 2003). Concerning colour properties, fMRI studies revealed that retrieving the name of a colour ordinarily related with an object (e.g., red in response to the word apple) elicited cortical responses in a region of the fusiform gyrus in the ventral temporal cortex contiguous to the occipital region related with colour's perception (Chao & Martin, 1999; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Martin, Wiggs, Ungerleider, & Haxby, 1996; Wiggs, Weisberg, & Martin, 1998). Converging results supporting this claim come from studies on colour imagery (Howard et al., 1998) and on colour–word association in response to auditory words (Paulesu et al., 1995).

These results are also supported by clinical studies documenting a double dissociation between people with achromatopsia that showed preserved ability in colour imagery (e.g., Shuren, Brott, Schefft, & Houston, 1996), and patients with colour agnosia, that showed an impaired knowledge of object-associated colours concurrent with normal colour vision (e.g., Miceli et al., 2001; Stasenko, Garcea, Dombovy, & Mahon, 2014).

These findings support the embodied cognition framework, as the regions involved when retrieving colour information are anatomically close to the regions previously identified as underpinning colour perception. Moreover, Beauchamp, Haxby, Jennings, and DeYoe (1999) and Simmons et al., (2007) showed that the activation of colour-related brain areas is sensitive to the demands of the task. When colour-selective cortex was mapped in a task requiring passive evaluation of coloured versus grayscale stimuli (e.g., Chao & Martin, 1999; McKeefry & Zeki, 1997; Zeki et al., 1991), neural response was restricted to the occipital cortex. However, when colour-selective cortex was studied using a more demanding task requiring participants to make judgments about differences in hue or with a property-verification task, activity extended from the occipital cortex to the fusiform gyrus (Beauchamp et al., 1999; Simmons et al., 2007). Thus, in support of the embodied-cognition framework, these data indicate that the processing system supporting colour perception includes both lower-level regions that mediate the sensation of colour and higher-order regions that mediate both perceiving and storing colour information related to object-colour association as well. Behavioural data have demonstrated that colour, together with shape, can be encoded as object property to in turn encode object representation. In the study of object recognition, in particular, this claim has received much attention. Traditionally, classic theories suggest that objects are recognized on the basis of shape, largely ignoring the role of colour information (Biederman, 1987). More recently, an ample body of empirical investigations suggests that colour information contributes to object recognition, and that colour should be integrated in object recognition models (for a review see Bramão, Reis, Petersson, & Faísca, 2011; Tanaka & Presnell, 1999; Tanaka, Weiskopf, Williams, & Tanaka, 2001). Particularly relevant to the focus of this thesis is the study of Naor-Raz, Tarr and Kersten (2003) in which authors indicate that colour is an intrinsic property of an object's representation, associated to object shape, and represented at multiple levels (including visual, conceptual, and semantic levels). Specifically, they used a variation of the classic Stroop paradigm in four experiments. In experiment 1, participants were required to name the colour as fast as possible, regardless of the object. Eight objects with highly diagnostic colour were used, and each object was presented either with their typical colour (e.g. yellow banana) or atypical colour (e.g. purple banana). Results showed that response times of typical colour objects were faster in comparison to atypical ones. A reverse pattern of results was obtained in experiment 2, in which the nouns of the same objects were used. Again, participants had to name the colour of the words (i.e. banana was shown either in yellow or purple letters), regardless of the nouns of the object which they referred to. Results showed an interference effect (i.e. reverse Stroop effect), with slower response times when participants named the typical colour as compared to the atypical ones. On the basis of these results, the authors argued that colour-shape associations arise from different forms of object representation. They hypothesized that pictures automatically recruit visual representations of objects while nouns automatically recruit lexical and conceptual representations, and both levels of representation include colour and its association with the object shape. In order to investigate the nature of these colour-shape associations further, the authors performed an additional experiment[1]. In this last experiment, participants had to perform a colour-naming task following by a lexical decision task (participants indicated if the word was grammatically correct or was a non-word). Words presented in this test phase could either be semantically related or semantically unrelated to a specific item shown during colour/object-tasks or were non-words. Moreover, both object pictures and object nouns were presented to participants. Results showed a prime effect only when participants previously encountered objects specified as words, even if they only had to name the colour in which words were presented. The authors interpreted their results as evidence that colour is an intrinsic component of visual representations of objects (rather than simply aiding segmentation or other precursors to object recognition). Visual access to associated object shape leads to enhanced colour naming (Experiment 1), while conceptual and lexical access to associated object shape leads to impaired colour naming (Experiment 2 and 4). Converging evidence was also obtained in an EEG study

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[1] Experiment 3 is a control experiment designed to clarify the different results obtained by Klein (1974).

(Martinovic, Gruber, & Müller, 2008). In experiment 3, the authors used the same stimuli employed in the study previous mentioned, and they found that a more negative N350 (that is a later component linked to object representation) was evoked with atypical coloured objects as compared to typical coloured objects, reinforcing the idea that colour is an intrinsic object property.

1.5 Language and sensorimotor recruitment

The embodied view of cognition assumes that language comprehension makes use of the neural systems ordinarily used for perception, action and emotion (Barsalou, 2008; Barsalou, Pecher, Zeelenberg, Simmons, & Hamann, 2005; Gallese & Lakoff, 2005; Glenberg & Kaschak, 2002; Pulvermüller, 2002). On the base of embodied language view, it has been hypothesized that understanding the semantic content of action-related linguistic material entails the activation of the motor system. This approach disagrees with the standard approach of language understanding, that is basically a-modal and nested in specifically specialized neural structures (e.g. Chatterjee, 2011; Fodor, 1975; Mahon & Caramazza, 2005, 2008; Pylyshyn, 1984).

1.5.1 Verbs

Works focussed on processing of verbs referring to action, presented alone or combined in sentences, have provided widely evidence for a recruitment of the motor system during language understanding. For example, neurophysiological studies demonstrated that reading or hearing action verbs associated with a specific effector (e.g. grasp, kick), results in somatotopic activation of correspondent motor areas (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, Härle, & Hummel, 2001; Pulvermüller, Shtyrov, & Ilmoniemi, 2005; Tettamanti et al., 2005); other studies, adopted transcranial magnetic stimulation techniques, showed specific modulation in the motor evoked potential (MEP) related to the muscle involved in the execution of the action expressed in a sentence (Buccino et al. 2005).

Other evidence comes from EEG and magneto-encephalography (MEG) studies. These studies showed that the recruitment of pre-motor and motor areas during the elaboration of verbs referring to concrete actions is quite early, occurring at 150–170 ms after the visual or auditory presentation of linguistic stimuli (Pulvermüller et al., 2001; Pulvermüller et al., 2005a; Pulvermüller et al., 2005b; for review see Pulvermüller et al., 2009). Converging evidence from behavioural studies have shown that within the first 200ms participants slow down the motor responses when they processed and at the same time they have to solve a semantic task (Buccino et al., 2005; Boulenger et al., 2006; Sato et al., 2008; Dalla Volta et al., 2009; see also de la Vega et al., 2014). Moreover, a recent MEG study (Klepp, Niccolai, Buccino, Schnitzler, & Biermann-Ruben, 2015) shed light to neural correlates of this slowing down of motor responses. It seems to be imputable to suppression of beta rhythm that is related to preparation and execution of actual movements in the same time window.

Other evidence had been obtained from behavioural studies showing, for example, that when the response requires a movement in the same direction of the described action, a modulation of reaction times occur (e.g., Glenberg & Kaschak, 2002). This action-sentence compatibility effect (ACE) arises when the movement is performed soon after the comprehension of the sentence or right before its end (Kaschak & Borreggine, 2008). ACE seems to be time-locked to the understanding of the action verb or to a post-verbal adverb when the adverb specify how the action is performed (Taylor & Zwaan, 2008). **Moreover, other evidence in this direction comes from studies that have manipulated the goal of the action and the effector involved in the response (Borghi & Scorolli, 2009; Scorolli & Borghi, 2007).**

It has been recently proposed that the mechanism through which action-related verbs could elicit the motor representations for action itself can be explained in terms of the mirror neuron system (Buccino et al., 2005; Sato et al., 2008). Mirror neurons are a set of neurons found in premotor and parietal cortices of monkeys and humans which are active both when an individual performs hand, mouth or foot goal-directed actions (e.g., grasping or sucking) and when he observes another individual performing similar actions or hears the sounds that these actions produce (Di Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996; Buccino et al., 2001; Kohler et al., 2002; Ferrari et al., 2003). It has been demonstrated that most of mirror neurons in the premotor cortex selectively discharge when a specific motor act is performed on an object (e.g., Di Pellegrino et al. 1992; Rizzolatti et al., 1996). For example, different mirror neurons are activated by the motor act of grasping performed with different types of hand grip depending on the size of the grasped object, such as the precision grip (which implies the opposition between the index finger and the thumb, and is used for grasping small objects), and the power grip (which implies the opposition of all the fingers, the palm and the thumb, and is used for grasping big objects). Since its discovery, the mirror neuron system has thought to match observed action with its motor representation in the observer, both in terms of muscles involved and temporal progress of the action. Thus, it is considered essential to action understanding and motor learning (Jeannerod, 1994).

1.5.2 Nouns

As we have seen, the activation of the motor cortex in action-related language comprehension has been extensively documented by studies that focused on processing of verbs referring to common motor behaviour. Similarly, studies on nouns understanding (Gough et al., 2012; Marino, Gough, Gallese, Riggio, & Buccino, 2013; Tucker & Ellis, 2004, Glover et al. 2004) have documented the activation of the motor system driven by nouns of manipulable objects, in analogy with the results showed by the studies about verbs understanding (see previous paragraph). Nouns of objects graspable with precision or power grip were used as stimuli. Participants were required to perform their responses through pantomime the same kinds of grip. The results showed that there is response facilitation when the same prehension required for manipulating the objects denoted by nouns is coherent with that actually used to respond; on the contrary, there is interference when the kinds of prehension are incompatible. Similar findings were obtained by Bub, Masson, and Cree (2008) with gesture-imitation task, in which the distinction between volumetric and functional gestures is obtained also with the nouns of graspable objects (see Size section for the definition). Moreover, another evidence, that language comprehension requires a simulation process coupling perception and action, comes from the study of Scorolli, Borghi and Glenberg (2008). The authors examined the effect of the object weight when participants read sentences describing the lifting of different weighted objects (e.g. a pillow or a tool chest), in a bimanual lifting task (i.e. participants lift a heavy or a light box with both hands after having read the sentence). Results of kinematic parameters reveal that the weight of the object is also simulated when we understand the meaning of nouns presented in a sentence.

Other evidence concerned nouns understanding have been obtained with linguistic categorization task (i.e., selecting whether nouns define abstract objects or define objects to be used with the hand or the foot). The response was required early (150ms) or delayed (1150ms) after presentation of nouns, and participants had to respond with their right or left hand. The results show that interference effects emerge only at 150ms, and solely when the task is performed with the right hand, which is controlled by language-dominant hemisphere (left motor cortex, Marino et al., 2013). In a TMS experiment (Gough et al., 2012, see also Cattaneo, Devlin, Salvini, Vecchi, & Silvanto, 2010 for similar results), participants had to read object words referring to either graspable or non-graspable artefacts (e.g. cup or airplane) or natural (e.g. apple or ocean) entities. The impulse was applied on the cortical area of the first dorsal interosseous (FDI) muscle of the right hand at 150 ms after noun presentation. The results show a different pattern of MEPs between nouns referring to graspable in comparison to nouns referring to non-graspable objects. Moreover, results showed greater MEPs with nouns denoting graspable artefact as compared to nouns denoting natural graspable objects. Similar results have been collected by means of fMRI (Rueschemeyer, van Rooij, Lindemann, Willems, & Bekkering, 2010). Nouns referring to graspable objects with an explicit functional use (e.g. hammer) elicited greater activation in the frontoparietal sensorimotor systems in comparison to graspable object nouns that do not have any specific functional use.

It has been very recently proposed that in the same way that mirror neurons could underlie processing of action-related verbs, canonical neurons could underlie processing of nouns of graspable objects (e.g., Marino et al., 2011). Canonical neurons are a set of neurons found in the ventral premotor cortex and in the anterior intra-parietal sulcus of both monkeys (Rizzolatti et al., 1988; Murata et al., 1997) and humans (Grézes et al., 2003) that have been shown to respond during the perception of objects which can be manipulated. Most of canonical neurons selectively discharge for objects of specific shape, size and orientation (Murata et al., 2000). The canonical system has thought to reflect sensorimotor transformations for actual manipulation and, thus, could represent the neural counterpart of the Gibsonian concept of object affordances (Fischer & Dahl, 2007; Philips & Ward 2002; Tucker & Ellis, 1998; Ellis and Tucker, 2000)

1.5.3 Adjectives and adverbs

Adjectives and adverbs are words that modify or give more information about other words. Specifically, adjectives explicit characteristics of nouns and pronouns (e.g. *red* apple, *small* apple), while adverbs can explicit characteristics of verbs, adjectives and other adverbs (e.g. he runs *slowly*). Few studies investigated how the meaning of these words are able to modify the sensorimotor activation during language understanding.

Concerning adjectives, only the study of Gough, Campione and Buccino (2013) investigated the motor activation elicited by adjectives, performing a TMS study in which adjectives (without any nouns), expressing positive vs negative pragmatic properties, were presented. Results showed that participants' MEPs of the first dorsal interosseous muscle (FDI) were reduced (during the first block of the trials) when participants processed positive adjectives. Conversely, the MEPs of the FDI were increased when participants read negative adjectives. The opposite pattern of results was found in the MEPs of the extensor communis digitorum (EC). The muscles recorded are involved in approach and grasping actions (FDI) and in releasing and avoidance actions (EC), respectively. The authors suggested that the described modulations of the motor system reflect the motor experience (or the motor competence) associated with the adjectives during the acquisition of language, that later subserves the comprehension of the meaning conveyed by that adjective in a variety of contexts. However, there is a lack of experimental evidence about the contribution of adjectives on motor modulation activated by nouns.

Concerning adverbs, Taylor and Zwaan (2008) have observed that when we read sentences, the action compatibility effect can be time-locked to the comprehension of the verb that defines the action or extended the post-verbal adverb only when specify how the action is performed (e.g. slowly or quickly), maintaining focus on it. Adverbs coding for different elements of the described situation on the other hand, shift the focus away from the described action, leading to the termination of the simulation process.

Effects of words qualifying object properties on kinematic parameters of reach-to-grasp movements were also found by Gentilucci and colleagues (2000). In their task, participants had to perform a precision grip on a small block on which a word was written. The word could be an adjective denoting size (small, big), colour (green, red) or location (high, low). The word could also be an adverb specifying a spatial property (near, far or up, down). The authors found that size adjectives had a direct effect on the grip components of a reach-to-grasp movement. With regard to the other adjectives, the results were less clear. In contrast, the adverbs directly affected the reaching component of grasping. As a whole, these results suggest that the meanings of adjectives and adverbs can be integrated into the planning and execution of reach-to-grasp movements directed towards a real object.

As discussed so far, processing of action-related linguistic material parallels visual processing of motor behaviour and action-related objects, as both recruit the motor system. There are, however, important differences between vision and language. When we observe an action or look at an object, each of the features is immediately fully specified. For example, when we observe an individual performing a reaching-to-grasp movement directed towards an object, we see not only how the grasping hand moves or the context in which the movement is performed, but also the location of the object as well as its size and orientation. This enables us to activate a detailed motor program in which the parameters of the component of reaching (e.g., hand velocity and movement amplitude) and the parameters of the grasping component (e.g., hand posture and orientation) are entirely specified. In contrast, when we understand a sentence describing a reaching-to-grasp movement directed towards an object such as for example 'James grasps the cup' it is not clear how the subject's hand moves, the context in which the action is performed, the object position and so on. Nevertheless, an activation of a motor program still occurs.

1.6 How grasp compatibility effect arises?

Recently it has been proposed that compatibility effects related both by visual objects and words may be generated by *double neural route* of the control of behaviour (2000). In the TRoPICALS computational model (*Two Routes, Prefrontal Instruction, Competition of Affordance, Language Simulation* Caligiore, Borghi, Parisi, & Baldassarre, 2010), the authors replicated the experimental results of Tucker and Ellis (2004) and Borghi, Glenberg, and Kaschak (2004). The results come from simulation experiments of the human behaviour, taking into account the functional and architectural constrains of the human brain, the constraints deriving from reproducing the response observed in specific experiments, the constraints involved within the requirement to simulate a realistic participant with a realistic sensory response (e.g. simulating realistic movements of a three-dimensional arm and hand or trichromatic colour perception), performing the task in a realistic environment (e.g. realistic RGB pictures), and finally, the constraints related to requirement that the model should reproduce and explain learning processes of real participants (Caligiore et al., 2010). Specifically, the model underlines that the compatibility phenomena are modulated by top-down bias from prefrontal cortex (PFC). The model is based on four general principles that are:

- visual input is processed along the ventral and dorsal stream (Goodale and Milner, 2008), taking into consideration both the visuomotor transformations of object affordances into potential actions (Rizzolatti, Luppino, & Matelli, 1998) and how and where information on context and object categories are stored and processed (Borghi, Glenberg, & Kaschak, 2004);
- the action selection is based on PFC feedback. The prefrontal cortex is able to modulate, through the ventral stream, the selection of affordances on the basis of the current goals of the agent (Grill-Spector & Malach, 2004; Weiner & Grill-Spector, 2012);
- this selection can be generated by the competition of different affordances (Fuster, 2001; Miller & Cohen, 2001) based on PFC bias; information on the actions afforded by the object and information from PFC on the agent's goals are based on a neural competition (Cisek, 2007), that causes the action initiation.

- The simulation process (Gallese, 2008) of the object referent (i.e. the noun of the object). The simulation process is implemented through a Hebbian correlation learning rule that generates associations between active neurons corresponding to the words and internal simulations (e.g., the representations of the categories of objects and the representations of the aspects of objects that guide action, such as their shape)

When these mechanisms work in an integrated fashion, they explain the RTs found in compatibility effect experiments, both with visual object and object referent (words).

In a revised version of the model (Caligiore et al., 2013), the authors are able to integrate in the model the effect of distractors (see discussion of Experiment 2 for further details), going to biological realistic model. The main improvement of the revised TRoPICALS model is the implementation of two parallel circuits connecting the PFC to motor areas, one excitatory and one inhibitory. Both are involved in the task responses when multiple affordances (i.e. multiple objects) are presented in the visual array. The two circuits provide a positive bias in favour to action required by the task, and a negative bias negative in order to inhibit the action automatically evoked by the distractor (Cisek, 2007; Erlhagen & Schöner, 2002).

For our purposes, this model seems do not take into consideration the further subdivision of dorsal stream in dorso-dorsal and ventro-dorsal streams (Rizzolatti, 1998), and the relative fine-grained proposal of stable and variable affordances (Borghi & Riggio, 2009, 2015), especially for what happens during language comprehension. In other words, in the TRoPiCAL model the distinction between variable aspect of the interaction (that are not represented in language) and the stable ones (that are simulated and re-activated during language comprehension), is not take into account.

We believe that the model is not in contrast with our findings (see also the conclusion) but, in order to achieve likelihood to the realistic human behaviours, the model could benefit from the integration with the concepts of stable and variable affordances, and with the recent findings of their representation in ventro-dorsal and dorso-dorsal streams (Sakreida et al., 2016)

1.7 Research Overview

In the following chapters, I will present first evidence to support the hypothesis that colour affects both sensorimotor representation and simulation. These evidence will be discussed together with the notion that objects and their referents can recruit the motor system and activate action-relevant object information. In addition, evidence from a new behavioural task that object colour modulates motor response will be shown and compared to what happens with dangerous objects, in the visual domain. To further extend these results to object representation, evidence with language materials will be presented. These results show that colour can affects the object sensorimotor simulation. In addition, these results highlight the difference between the sensorimotor[2] simulation related to language understanding and the direct recruitment of the motor system by visual objects (at least for natural objects category).

In chapter two, three experiments will be reported. As in most affordance studies, in the first experiment a grasp compatibility task is used to examine the presence of compatibility effects, arising while observing and categorizing pictures of graspable objects for which either power or precision grips are the more appropriate actions. Unlike the classic studies, that are focused solely to the starting phase (i.e. selection of grasp), we investigated both the starting phase and the execution of the movement, since our experimental setup allow participants to perform the entire reach-to-grasp movement. Moreover, our response device does not require any hand or arm muscles activation (as for the most compatibility studies), avoiding the possible motor interference between the action required to press, for example, a key and the response action. The novelty both of the first and the second experiment (that will be presented shortly) consists in presenting objects both with their correct/typical colour and with their opposite/inappropriate colour. Such a manipulation has allowed to investigate the association between colour and shape in the occurrence of grasp compatibility effect. In the second experiment, the new task will be used. To directly test the effect of colour on movement, a different grasp compatibility task has been developed. In this task no previous categorization of the

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[2] Sensorimotor and motor simulation will be used interchangeably, intending the re-recruitments of some mechanisms and processes of the perception and motor system in order to understand language (Gallese & Lakoff, 2008; Borghi & Riggio, 2015)

object is needed, since a pre-specified grasp, driven by a linguistic cue, is required regardless the nature of the object. A visual object (with its correct or opposite colour) will be shown after the start of the reach-to-grasp, leading us to investigate the role of object colour in the re-recruitment of the motor system by the mere vision of the object. Finally, in order to validate this task, in the third experiment dangerous and graspable visual objects will be used, with the new task introduced above.

In chapter three, four experiments will be described. We will move from the visual domain to the language domain in order to extend the results obtained with visual objects and, moreover, to ascertain whether colour can be included in the stable affordances concept as size and shape (Borghi & Riggio, 2015). For all the next experiments, the same grasp compatibility task of the first experiment will be used. Experiment 4 was developed to assess and to replicate the grasp compatibility effect with object nouns. Experiment 5 aims to investigate how colour and dangerous (in language experimental section disadvantageous term will be used) adjectives modify the sensorimotor representation of objects expressed by their nouns. Experiments 6 and 7 aim at ruling out the possibility that the results of the previous experiments could be related, from one hand to a no integration between disadvantageous adjectives and objects nouns (Experiment 6 and 7), and from the other hand to a type II error (Experiment 7). In particular, in Experiment 6, we test an additional category of adjectives that explicit manipulative characteristics (i.e. shape and tactile features) which should be already simulated during the comprehension of the object noun. In other words, following the linguistic focus hypothesis (Taylor & Zwaan, 2008), we would expect that the motor simulation driven by object nouns continue until words motorically relevant (i.e. in this case adjectives) will be presented. Finally, in the last experiment (i.e. Experiment 7), a conceptual replication of Experiment 5 will be presented and discussed, also in the light of the difference of languages tested (Italian in Experiment 5 and English in Experiment 7).

Chapter Two
Is colour an integral part of object motor representation?

The human ability to interact with the environment requires a tight coupling between perception and action. A growing number of studies have provided evidence for a functional link between perceptual systems (most commonly vision) and action. Some of the most compelling evidence comes from studies that demonstrate how seeing a graspable object activates a set of potential hand movements associated with object manipulation (i.e. micro-affordances, Ellis & Tucker, 2000; affordances, Gibson, 1979). Activation of motor programs, that is representations specifying parameters of possible actions that can be taken (e.g. Cisek, 2006, 2007; Fadiga, Fogassi, Gallese, & Rizzolatti, 2000), through passive viewing of objects has been demonstrated in several tasks involving categorization (Anelli, Nicoletti, & Borghi, 2010; Gerlach, 2009), mental rotation (De'Sperati & Stucchi, 1997, 2000) and compatibility paradigms (Ellis & Tucker, 2000; Tucker & Ellis, 2004)

Behavioural evidence goes some way towards establishing that specific aspects of hand-object interaction are encoded in these motor programs, such as the type of hand posture required by those objects to be grasped (Ellis & Tucker, 2000; Tucker & Ellis, 2004) (which mainly pertains to object size) and the hand most suited for manipulation (Pappas, 2014; Tucker & Ellis, 1998) (which primarily pertains to object orientation). However, some aspect of how we experience the world has not been taken into account.

Specifically, one essential constituent of our experience of world is the colour. In the field of affordance studies, or broader in EC approach, colour has not received much attention, and generally speaking, it is usually considered as an abstract characteristic not directly related to objects in the world. However, some objects are frequently associated with a specific colour and this is particularly evident for natural objects (Hansen, Olkkonen, Walter, & Gegenfurtner, 2006; Price & Humphreys, 1989). As already introduced, we can report some common experience that can highlight the influence of colour in everyday life. For example, if we look at a ripe strawberry, the strawberry has not only a distinctive shape but also another distinctive property, that is its red colour. Likewise, if we imagine a strawberry, the imagined strawberry has a distinctive shape and colour. Moreover, if we have to decide to grasp a red strawberry or a green strawberry, we almost surely prefer to grasp the red one.

The main aim of the present thesis is to investigate whether and how colour has a pragmatic role in interaction with objects. To this end, we compare colour and dangerous information in the modulation of hand motor program activated by the observation of graspable objects. First of all, the rationale of colour manipulation of the stimuli will be presented. Afterwards, two experiments in which we investigate the role of colour in hand-object interaction will be described and discussed. Finally, a control experiment in which we manipulate another contextual aspect (the dangerousness of the object, e.g. spiky objects) will be presented and discussed in relation to colour experiments.

2.1 Experiment 1

The first experiment is aimed to assess whether object motor representation also included the object colour as well as the size and the shape. As discussed in the first chapter, certain objects have stable features that occur together with a certain regularity. That could be the case of size (and the associated grip) and colour of an object. If this is correct, many expectations can be drawn. First of all, we expect a compatibility effect between the visual object and the response grip, as frequently reported in literature (Elliot, 2015; Naor-Raz & Tarr, 2003; Witzel, Valkova, & Hansen, 2011).

Moreover, this compatibility effects may be modulated by the colour of the object. Specifically, if the colour-shape association is sufficiently strong, the compatibility effect should arise only with objects displayed with their usually correct colour. It is also possible that colour does not interact with compatibility, since colour processing might be involved solely in object recognition. In this case, we expect that colour will affect overall the response, leading to a better performance with correct colour objects as compared to opposite colour objects. Finally, the colour might impact differently on the two object categories, highlighting a different weight of the colour in object representation as preliminary showed by validation phase.

2.1.2 Method

2.1.2.1 Participants

Twenty-six (13 females; mean age = 24 ± 1.95 SD) participants took part in Experiment 1. All were right-handed as measured by a standard handedness inventory (Oldfield, 1971), had normal or corrected-to-normal vision and did not have any colour vision impairment, as assessed with the Ishihara's Test for Colour Deficiency (Ishihara, 1974). All were naïve as to the purpose of the experiment.

2.1.2.2 Ethics Statement

All participants were 18 years or older and prior to participating, they gave their informed consent, accordingly with the ethical standards of the Declaration of Helsinki.

Moreover, the experiment complied with the ethical standards of the Italian Psychological Society (AIP, see http://www.aipass.org/node/26) and Italian Board of Psychologists (see http://www.psy.it/codice_deontologico.html). As the experiment did not involve any use of pharmaceuticals or medical equipment and or clinical treatments, the approval from the Parma hospital ethics committee was deemed unnecessary.

2.1.2.3 Stimuli

Thirty-two validated object pictures were used: eight of natural objects graspable with a precision grip, eight of natural objects graspable with a power grip, eight of artefact objects graspable with a precision grip, and eight of artefact objects graspable with a power grip. Each picture was presented sixteen times, for a total of 512 trials. For the results of the validation see Appendix A.

2.4.4 Apparatus and Procedure

The experiment took place in a sound-attenuated and dimly illuminated room. The experimental apparatus consisted of an Elo-Entuitive 42'' monitor connected to a computer running E-Prime 2.0 software. Viewing distance was fixed at 57 cm by using an adjustable head- and chin-rest placed in front of the screen. The response device consists of three parts: two wood cylinders placed on top of each other, and a square starting base (10 x 10 cm). The dimension of the bottom cylinder is compatible with a power grasp (power cylinder: h = 14 cm, d = 6 cm), while the dimension of the top cylinder is compatible with a precision grasp (precision cylinder: h = 4 cm, d = 1.5 cm). The cylinders were placed at 43 cm from the chin-rest. The starting base was located centrally with respect to participants' body midline. All three parts of the response device were connected to an external USB device trigger through three separate capacitive sensors (see Figure 1).

Each trial started when the participant placed the palm of her/his right hand on the starting base. The device does not require pressure in order to detect the hand's presence. In this way, we avoided any muscle activation of the hand or arm, reducing the possible motor interference between the action required to press a key and the response action. When participants placed their right hand on the starting base, the fixation cross (bold courier new, 30-point size) appeared at the centre of the screen. The cross remained on the screen for a variable duration between 500 and 1000ms. Experimental stimuli replaced the fixation cross and remained on the screen until a response was provided. Participants had to categorize each object as natural or artefact by performing either a precision or a power reach-to-grasp movement (Grasp compatibility task, GR-task). Response grasps could be compatible or incompatible with the ones normally used to manipulate the objects. This experimental apparatus allows obtaining information about both the reaching and grasping phases. The mapping between the category of the object and the response on the device (power or precision cylinder) was counterbalanced across participants. The experimental task started with a practice session (40 trials). After the practice trials, the experimental trials were run. The participants were tested individually, and they were instructed to find the best compromise between speed and accuracy while performing the task.

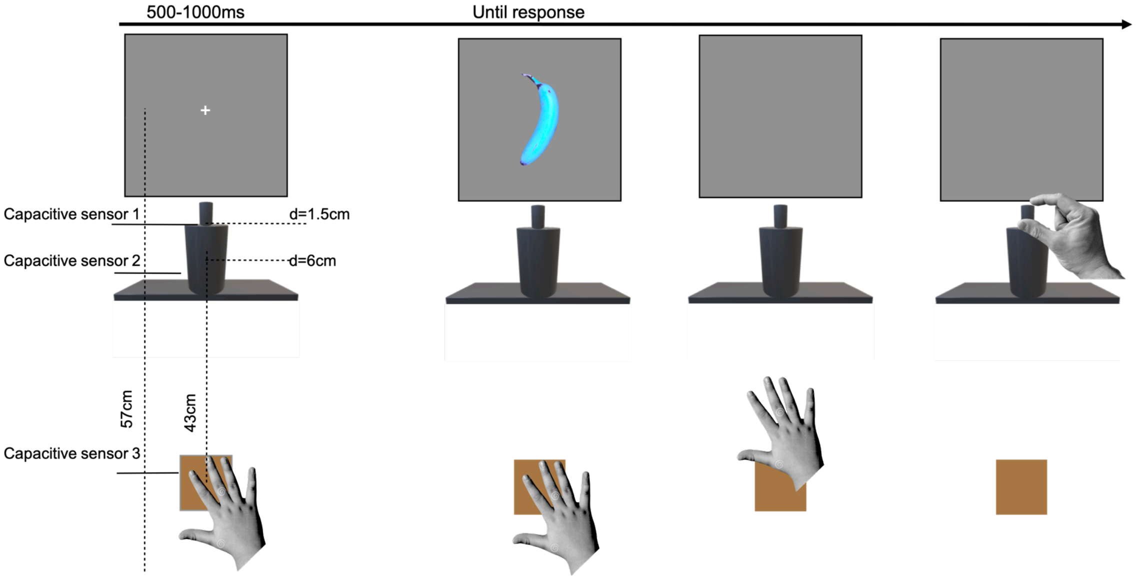

Figure 1. Experimental apparatus and trial time course of Experiment 1.

2.4.5 Analyses and Results

Data analyses were performed using R 3.4.4 (R Core Team, 2018), excluding from analyses the practice trials. Participants' Lift-off times[3] (LTs, ms), Movement times (MTs, ms), and error rate (ER) were recorded and analysed. The LTs were measured from stimulus onset to the lift of the hand from the starting base. The MTs were defined as the time difference between the end of the reach-to-grasp movement (the grasp of one of the two cylinders) and the hand lift from the starting position. Given the design of the experiments, with multiple observations for participants and stimuli, we performed the analysis on LTs and MTs using LMM, specifying the models with random effects for participants and stimuli, and including random slopes of each fixed effect (Barr, Levy, Scheepers, & Tily, 2013). The LMMs was computed using Afex package (Singmann, Bolker, Westfall, & Frederik, 2016). Pairwise post-hoc comparisons with Tukey HSD correction were performed on interaction effects when necessary. Moreover, estimated marginal means were used in order to test interaction effects based on planned comparisons, in order to assess directly the hypothesis.

Error Rate. Participants performed 1.44% (172 trials) of incorrect classification showing a good accuracy in the discrimination task. All participants performed less then 10 incorrect classification (min = 0, max = 9). No other statistic will be applied since ER is below 5%.

Lift-off times. LTs of correct trials were considered for the analysis. 334 datapoints were a-priori removed from the dataset as symptomatic of anticipatory responses (<100ms, 2.81%), according to standard methods of treating with response times (Luce, 1986; Whelan, 2008). Only the LTs included in 2.5 standard deviations, calculated for each participant (data loss: 2.4%, 278 trials), was selected. The remaining distributions of LTs were inspected to evaluate deviations from normality (see Figure 2)

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[3] The terms *Lift-off times* we have been chosen to specify the type of movement required of the participant, but they are analogous to classic Release times.

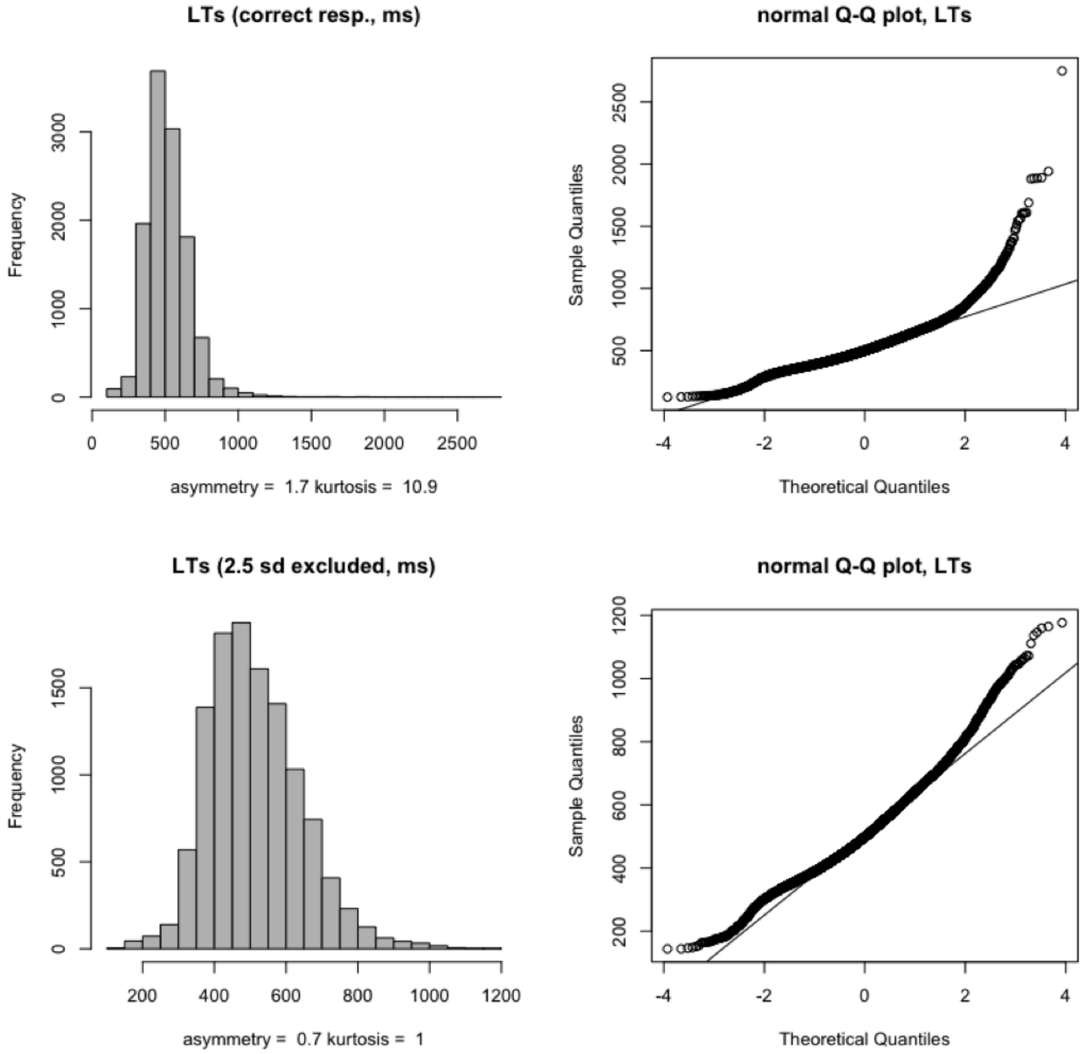

Figure 2. Distribution of LTs in Experiment 1. In the upper panels, are reported the distribution of raw LTs with the associated Q-Q plot. In the bottom panels, is reported the distribution after removing values above and below 2.5 standard deviations for each participant. Below both distributions, graphs are reported with the values of asymmetry and kurtosis.

A linear mixed model was carried out on LTs, with Compatibility (2 levels: compatible and incompatible), Object Category (OC, 2 levels: natural and artefact), Colour (2 levels: correct and opposite), and Response Mapping (RM, 2 levels: power-to-natural and power-to-artefact) and all their interactions as fixed effects. Stimuli and Participants nested in RM were set as random effects.

The model reveals the fixed effect of Compatibility, with faster responses for compatible trials (M = 512ms, SE = 1.7ms) than incompatible (M = 516ms, SE = 1.8ms). Moreover, the model showed a reliable interaction between OC and Colour, with faster LTs when natural objects were showed with their correct colour compared to other conditions (see Table 2 and Figure 3).

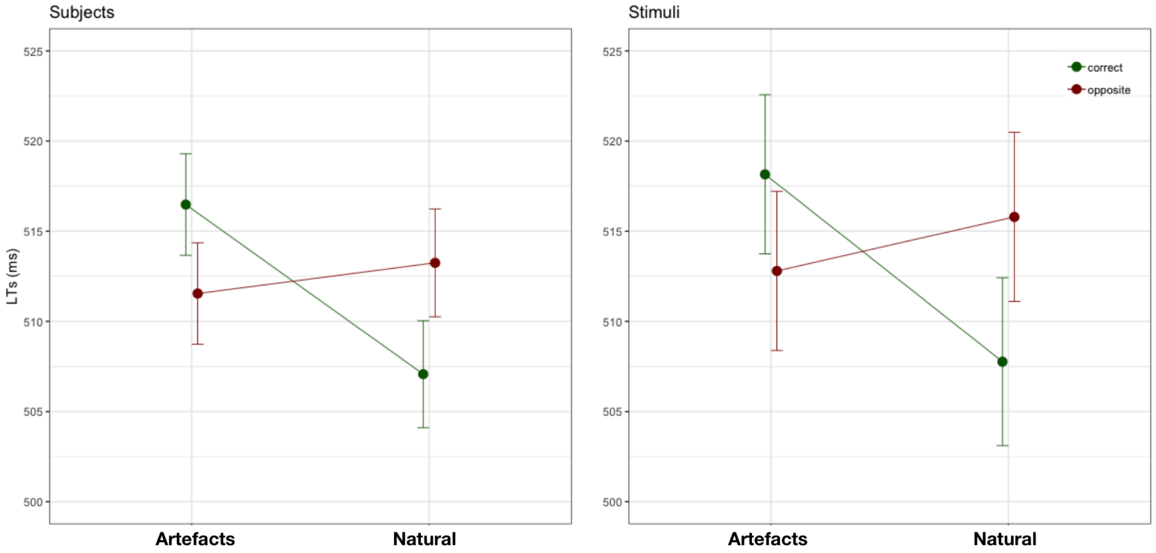

Figure 3. LTs estimated effects for Experiment 1 are shown in function of the Object Category and Colour factors. All error bars are 95% CI, computed with the Morey method . Intervals that do not overlap can be interpreted as evidence of a difference between conditions. Left and right panels show the model computed with subjects and with stimuli, respectively, as random intercepts. Data show the same trend, but this effect is generalizable to the population but not to stimuli.

Post-hoc comparisons, with Tukey HSD correction, confirm the significant difference for the natural objects with correct colour (p-adj. = 0.03) and also reveals the difference between artefacts and natural objects displayed with correct colour (p-adj.= 0.008). Finally, the model revealed a significant interaction between RM and OC, with overall faster LTs with the RM 1 as compared to RM 2 and also with a difference between natural and artefact objects only in the RM 2 (p-adj. = 0.04, see Table 1 for descriptive statistics).

	Colour				**Response Mapping**			
	Correct		**Opposite**		**Power-to-natural**		**Power-to-artefact**	
	Means	*SE*	*Means*	*SE*	*Means*	*SE*	*Means*	*SE*
Artefact	518	2.41	513	2.35	503	1.93	528	2.76
Natural	508	2.37	516	2.53	502	2.12	521	2.72

Table 1. Descriptive statistics for the LTs interactions.

Movements Times. The MTs distribution was subjected to visual inspection, showing a marked deviation from normality. In order to reduce skewness and kurtosis, an iterative Box-Cox procedure (2008) was employed. The Box-Cox procedure revealed that meaningful lambda transformation parameter, that best yielded a reduction of skewness and kurtosis across participants, was lambda = 0, which corresponds to the logarithmic transformation of MTs.

The transformed MTs was submitted to a new LMM with the same fixed and random effects as the LTs model. Results revealed the reliable fixed effect of Compatibility and the interaction between OC and RM (see Table 2), although post-hoc comparisons did not confirm any significant difference (all ps-adj. > 0.4).

	Lift-off Times				**Movement Times**			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
OC	514	511.63 – 516.35	1.50	0.145	345	342.87 – 347.90	-0.71	0.481
Compatibility	510	508.86 – 511.88	-2.35	**0.019**	342	340.04 – 343.03	-6.24	**<0.001**
Colour	512	510.39 – 513.42	-0.36	0.718	345	343.77 – 346.76	-1.35	0.176
RM	501	459.60 – 543.27	-0.50	0.620	350	320.97 – 378.02	0.22	0.828
OC:Compatibility	512	510.86 – 513.88	0.24	0.808	347	345.86 – 348.86	1.39	0.165
OC:Colour	515	513.44 – 516.46	3.59	**<0.001**	346	344.52 – 347.51	-0.37	0.708
Compatibility:Colour	512	510.69 – 513.71	0.02	0.986	347	345.65 – 348.64	1.11	0.268
OC:RM	510	508.85 – 511.87	-2.37	**0.018**	348	346.46 – 349.45	2.17	**0.030**
Compatibility:RM	512	509.97 – 514.69	0.12	0.906	345	342.76 – 347.79	-0.80	0.431
Colour:RM	512	510.20 – 513.22	-0.61	0.541	347	345.49 – 348.48	0.90	0.369
OC:Compatibility:Colour	512	510.48 – 513.51	-0.24	0.808	347	345.90 – 348.89	1.44	0.150
OC:Compatibility:RM	514	511.88 – 516.60	1.71	0.098	349	346.17 – 351.20	1.86	0.073
OC:Colour:RM	512	510.56 – 513.59	-0.14	0.889	346	344.77 – 347.76	-0.05	0.963
Compatibility:Colour:RM	512	510.36 – 513.38	-0.41	0.682	347	345.10 – 348.10	0.39	0.695
OC:Compatibility:Colour:RM	512	510.79 – 513.81	0.15	0.878	346	344.49 – 347.48	-0.41	0.681
Random Effects								
σ^2	6863.94				6727.72			
$\tau_{00\ \text{stimuli}}$	27.16				33.73			
$\tau_{00\ \text{ss:rm}}$	10921.07				5069.21			
Observations	11634				11634			
Marginal R^2 / Conditional R^2	0.008 / 0.618				0.004 / 0.434			

Table 2. LTs and MTs model tables. Reliable values are reported in bold.

2.1.3 Discussion

Results of Experiment 1 are consistent with previous findings reporting grasp compatibility effects for seen objects associated with a power or precision grip. Similarly to literature results, in the present experiment the main effect of Compatibility was significant, indicating faster responses of compatible trials compared to incompatible ones. Nonetheless, the grasp compatibility effect is detectable in the MTs, and it seems to indicate that the established coupling between object size object and the appropriate hand motor program influences also the reaching phase of the movement (see Singmann et al., 2016). Moreover, no interaction arises between Compatibility and RM, showing that for both power and precision objects the compatibility effect is reliable. The results of Experiment 1 fail to reveal a direct relationship between grasp compatibility effect and colour, both in the reaching phase (MTs) and in planning phase (LTs).

Nevertheless, results highlight faster responses when natural colour objects are the target stimulus. At first glance, the simplest explanation is that this facilitation may be related to faster recognition when natural objects are presented in their correct colour. It is now widely accepted that colour can be used as relevant feature in object recognition and categorization (Bramão, Reis, Petersson, & Faísca, 2011; Price & Humphreys, 1989; Tanaka & Presnell, 1999; Tanaka, Weiskopf, & Williams, 2001; Therriault, Yaxley, & Zwaan, 2009), specially for natural objects (Price & Humphreys, 1989). However, in object recognition studies, a semantic classification (e.g. natural vs artefact), naming or an object-name verification are usually required (for a review see Gerlach, 2001; Laws & Hunter, 2006; Price & Humphreys, 1989). These tasks do not require to program and execute any movements related to the object in order to successfully complete the task. In our study, the colour facilitation emerges when participants had to categorize objects by planning and executing grasp movements, and specifically during the first phases of these processes. The type of task favours an alternative explanation of this result. Different tasks impose different cognitive demands (Humphreys, Price, & Riddoch, 1999), and in this case not only the recognition process may be involved, but also easier access to object motor representation (for natural objects) when a salient feature is correctly displayed. In other words, our task demands to identify the category of the objects performing a reach-to-grasp movement in order to categorize a stimulus correctly. The movement might make salient a set of objects characteristics, including the typical way of grasping the object (i.e. the grasp affordance) and the also the colour for natural objects. This could lead to facilitating the start of reach-to-grasp movements when these characteristics are correctly showed.

In order to disentangle the recognition process from the sensorimotor representation hypothesis, we developed a different task in which motor activation of grasp is independent of the object recognition and categorization.

2.2 Experiment 2

People are able to adapt their ongoing movement in response to a rapid change in the visual array and, recently, there are establishing compelling evidence for this point (Archambault, Ferrari-Toniolo, Caminiti, & Battaglia-Mayer, 2015; see also Elliott et al., 2010). As well as the start of direct goal movements (as grasping a cup to drink), recent studies highlight a similar complex mechanism when we make online corrections to counter small disturbances of the limb or altered visual feedback (Scott, Cluff, Lowrey, & Takei, 2015). Such goal-directed feedback seems to be generated by common neural circuits associated with the initial stages of the movements (Sarlegna & Mutha, 2015). These common mechanisms and neural substrates afford a highly responsive system to maintain goal-directed control or rapidly update and select new motor actions in order to interact in a complex world successfully.

Moreover, kinematic studies have shown that an irrelevant stimulus, simultaneously presented, but with different features, in comparison to the target stimulus, modifies the reach-to-grasp response on the target stimulus (e.g. Sarlegna & Mutha, 2015), suggesting that irrelevant stimulus features are processed even though they are irrelevant to the goal. In this field of study

As a stronger test of the hypothesis that object motor representation also includes the colour of the object, and that its role is not only confined to object recognition, we performed a second experiment in which an irrelevant visual object was shown during the execution of a pre-specified reach-to-grasp movement. The task will be thoroughly described after this section, but some expectations can be discussed here. If the visual object is processed even if irrelevant for the pre-specified grasp, it is reasonable to expect a grasp compatibility effect in the reaching component of the movement. Specifically, we expect a reversed grasp compatibility effect with a slowing down of the movement of the compatible reach-to-grasp condition due to a competition between the already underway motor program and the compatible motor program evoked by the object. Moreover, if colour is a relevant feature for motor object representation, we expect that objects with opposite colour reduce the grasp compatibility. Finally, whether the colour effect is related to object category (as in Experiment 1), we expect that the grasp compatibility effect should be modulated by the object category.

2.2.1 Method

2.2.1.1 Participants

Thirty (20 females; Mean age = 25 ± 3.88 SD) participants took part in Experiment 2. All were right-handed as measured by a standard handedness inventory (Oldfield, 1971), had normal or corrected-to-normal vision and did not have any colour vision impairment, as assessed with the Ishihara's Test for Colour Deficiency (Ishihara, 1974). All were naïve as to the purpose of the experiment. Two participants were replaced since the experimental apparatus did not record their responses.

2.2.1.2 Ethics Statement

All participants were 18 years or older and prior to participating, they gave their informed consent, accordingly with the ethical standards of the Declaration of Helsinki. Moreover, the experiment complied with the ethical standards of the Italian Psychological Society (AIP, see http://www.aipass.org/node/26) and Italian Board of Psychologists (see http://www.psy.it/codice_deontologico.html). As the experiment did not involve any use of pharmaceuticals or medical equipment and or clinical treatments, the approval from the Parma hospital ethics committee was deemed unnecessary.

2.2.1.3 Stimuli

All the same validated pictures were used as irrelevant stimuli: eight of natural objects graspable with a precision grip, eight of natural objects graspable with a power grip, eight of artefact objects graspable with a precision grip, and eight of artefact objects graspable with a power grip. Each picture was presented sixteen times, for a total of 512 trials.

2.2.1.4 Apparatus and Procedure

The experimental apparatus was the same used in Experiment 1. We modified the procedure. Each trial started when the participant placed the palm of her/his right hand on the starting base. When participants placed their right hand on the starting base, the fixation cross (bold courier new, 30-point size) appeared at the centre of the screen. The cross remained on the screen for a variable duration between 500 and 1000ms. A linguistic cue indicating which was the cylinder to grasp, replaced the fixation cross. The linguistic cues correspond to the dimension of the cylinders: grande (big) for the bottom cylinder and piccolo (small) for the upper one. During the execution of the movement, an object, with a size compatible or incompatible with the executed grip, appeared on the screen with two stimulus onset asynchronies (SOA) from the beginning of the movement (10 or 100ms) and remained until the grasp was completed. The two SOAs were selected in order to maximize, from one hand, the chance to correct the grasp (10ms SOA), and from the other hand, to have a control condition in which participants should not be able to correct their movement. In order to ensure that participants pay attention to the objects, we warned participants that at the end of the task, we would have asked them to remember as many stimuli as possible. The experimental task started with a practice session (40 trials). After the practice trials, the experimental trials were run. The participants were tested individually, and they were instructed to find the best compromise between speed and accuracy while performing the task. The experiment took place in a dimly illuminated and sound-attenuated room.

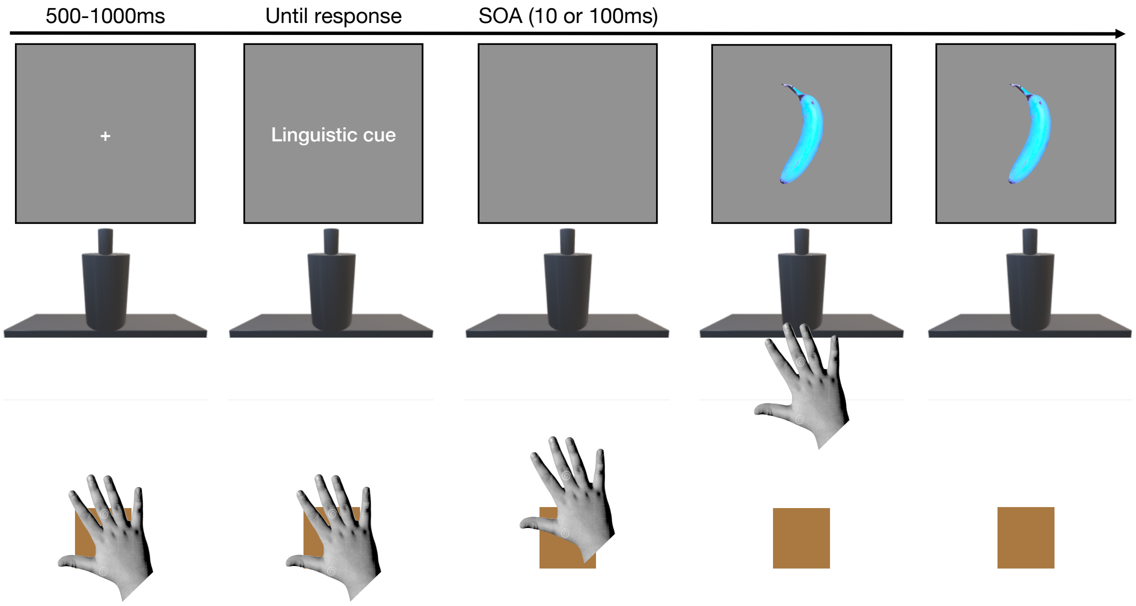

Figure 4. Experimental apparatus and trial time course of Experiment 2.

2.2.1.5 Analyses and Results

Data analyses were performed using R 3.4.4 (Ishihara, 1974), excluding from the analyses practice trials. Participants' Lift-off times (LTs, ms), Movement times (MTs, ms), and error rate (ER) were recorded and analysed. The LTs were measured from linguistic cue onset to the lift of the hand from the starting base. MTs were defined as the time difference between the end of the reach-to-grasp movement (the grasp of one of the two cylinders) and the hand lift from the starting position. Given the design of the experiments, with multiple observations for participants and stimuli, we performed the analysis on LTs and MTs using linear LMM. Concerning LTs, only the fixed effect of the linguist cue was checked, including also participants as random effect. In MTs model, we included as fixed effects SOA (two levels: 10ms and 100ms), OC (two levels: natural and artefact), Compatibility (two levels: compatible and incompatible) and Colour (two levels: correct and opposite), and all their interactions.

Furthermore, we specified the model with random effects for participants and stimuli and including random slopes of each fixed effect. The LMMs was computed using Afex package. Simple marginal means were used in order to test interaction effects based on planned comparisons.

Error Rate. Participants performed 1.74% (254 trials) of incorrect grasps showing good accuracy. All participants performed less then 6% (30 trials) incorrect grasps (min = 0, max = 28). No other statistics will be applied since ER is below the 5%.

Lift-off times. LTs in correct trials were considered for analysis. Moreover, given the design of the experiment we removed LTs below 100ms as anticipatory LTs (356 trials, 3.7%) and also MTs below 100ms (21 trials, 0.14%). Model did not reveal the effect of linguistic cue (Mpiccolo = 532ms, SE = 4.0; Mgrande = 535ms, SE = 2.2).

Movements Times. The MTs distribution was subjected to visual inspection, showing a marked deviation from normality (see Figure 5). MTs below and above 2.5 SD for each participant were excluded and considered outliers (301 trials, 2.15%).

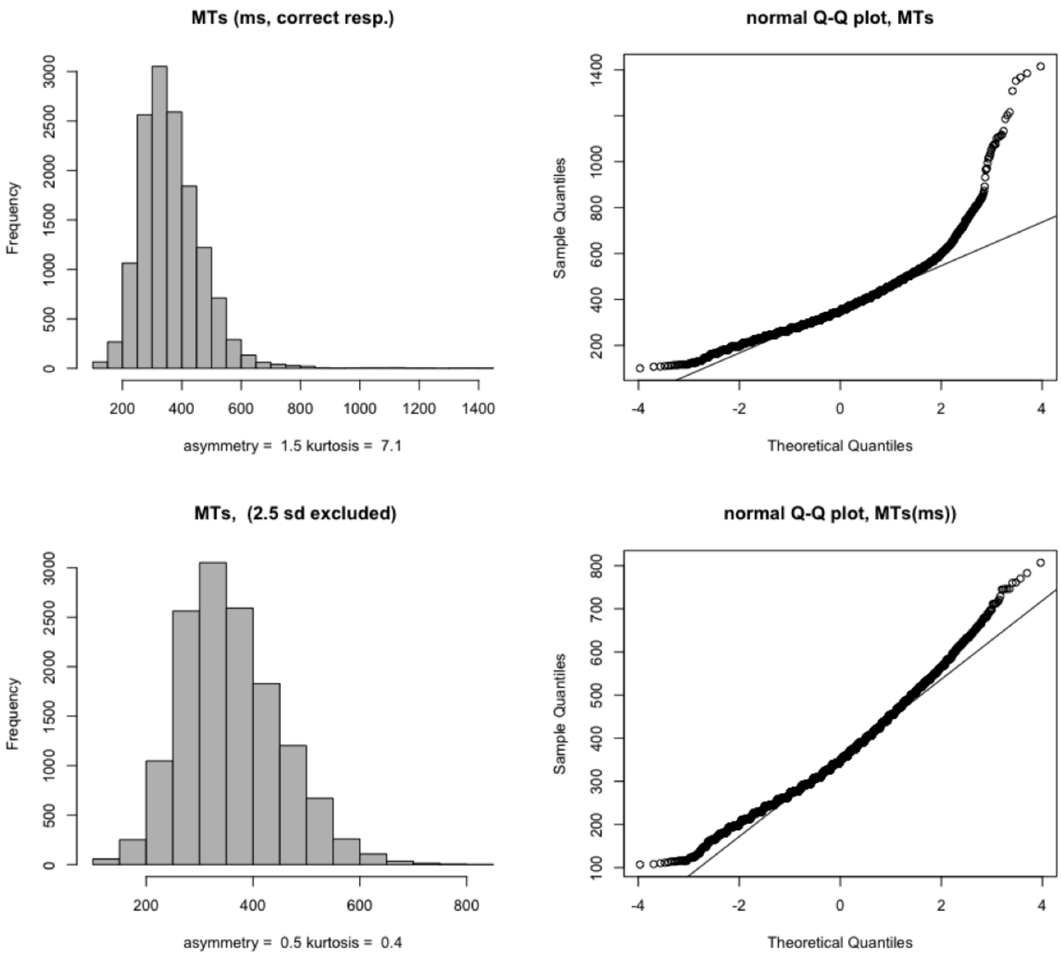

Figure 5. MTs distribution in Experiment 2. In the upper panels are reported the distribution of raw LTs with the associated Q-Q plot. In the bottom panels are reported the distribution after removing the values above and below 2.5 standard deviations for each participant. Below both distribution graphs are reported the values of asymmetry and kurtosis.

The remaining MTs were submitted to a new LMM as described above. The model revealed the reliable fixed effect of Colour (Mcorrect = 357ms, SE = 1.11; Mopposite = 361ms, SE = 1.12) and the critical interaction between Colour, SOA and Compatibility (see Table 4)

		SOA = 10ms		**SOA = 100ms**	
		Means	*SE*	*Means*	*SE*
Correct	compatible	360	2.21	357	2.3
	incompatible	355	2.22	356	2.2
	GC effect	-5		0	
Opposite	compatible	362	2.28	362	2.2
	incompatible	362	2.24	359	2.2
	GC effect	0		-2	

Table 3. Descriptive statistics for the MTs interaction among Compatibility, SOA and Colour. Below the compatibility conditions is reported the Grasp Compatibility effect (MTs $_{Incompatible}$ – MTs $_{compatible}$).

Compatibility simple contrasts showed that the grasp compatibility is only significant with 10ms SOA and Correct object colour (p-adj. = 0.006; Mcomp = 360ms, SE = 2.21ms; Mincomp = 355ms, SE = 2.22ms, see Figure 6 and Table 3). Otherwise no compatibility effects arise.

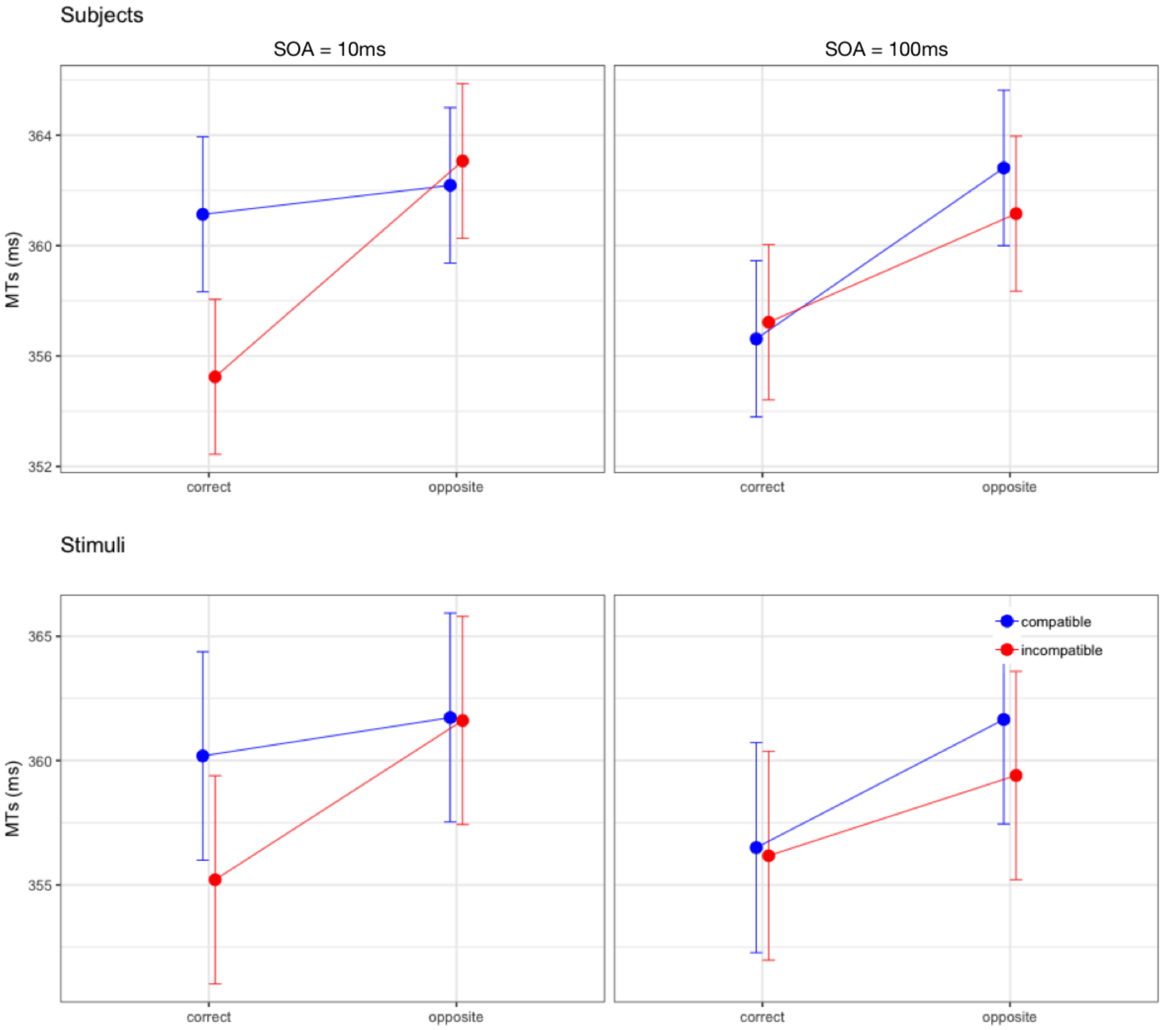

Figure 6. MTs estimated effects for Experiment 2 are shown in function of Compatibility (blue and red dots), Colour and SOA factors. All error bars are 95% CI, computed with the Morey method. Intervals that do not overlap can be interpreted as evidence of a difference between conditions. Upper and down panels show the models computed with subjects and with stimuli, respectively, as random intercepts. The data show the same trend, but the effect found is generalizable only to the population but not to stimuli.

	Movements Times			
Predictors	*Estimates*	*CI*	*t*	*p*
OC	359.70	358.58 – 360.82	-0.41	0.683
Compatibility	360.70	359.66 – 361.74	1.44	0.149
Colour	357.55	356.51 – 358.58	-4.52	**<0.001**
SOA	360.40	359.36 – 361.44	0.88	0.380
OC:Compatibility	359.83	358.79 – 360.87	-0.20	0.839
OC:Colour	360.32	359.28 – 361.36	0.73	0.466
Colour:Compatibility	360.51	359.47 – 361.54	1.07	0.283
OC:SOA	360.34	359.30 – 361.38	0.77	0.443
Compatibility:SOA	360.40	359.37 – 361.44	0.88	0.377
Colour:SOA	360.12	359.09 – 361.16	0.35	0.723
OC:Compatibility:Colour	359.92	358.88 – 360.96	-0.03	0.975
OC:Compatibility:SOA	360.53	359.49 – 361.57	1.12	0.263
OC:Colour:SOA	358.97	357.93 – 360.01	-1.82	0.068
Compatibility:Colour:SOA	361.06	360.02 – 362.09	2.12	**0.034**
OC:Compatibility:Colour:SOA	360.20	359.16 – 361.24	0.50	0.615
Random Effects				
σ^2		3830.50		
$\tau_{00\ \text{stimuli}}$		1.47		
$\tau_{00\ \text{ss}}$		4964.08		
Observations		13684		
Marginal R^2 / Conditional R^2		0.001 / 0.565		

Table 4. MTs model table. Reliable values are reported in bold

2.2.3 Discussion

As expected, the pattern of results emerged in Experiment 2 shows that participants' responses were modulated by object colour. We interpreted this effect as evidence for the role of object colour in the recruitment of motor system. When an object with the size compatible with the underway grasp is presented a reverse grasp compatibility effect arises. Specifically, at the start of the movement, objects with correct colour and with a size compatible with the executed grip slow the movement as compared to incompatible objects. It seems that only these objects recruit the motor system, leading to an interference effect, as compared to the opposite colour objects that overall slowdown the movement. Following the literature (Ellis, Tucker, Symes, & Vainio, 2007; Knight et al., 1999), these results are easy to explain in light of excitatory and inhibitory mechanisms proposed to explain the inhibitory effect induced by graspable distractors. Our task produces first a preliminary activation of motor program related to the size of the manipulandum, and after that, when the object appears at the early SOA, a second motor program related to the size of the object is evoked. These two motor programs can compete with each other (e.g. the linguistic cue requires to perform a power grip and the object elicits also a power grip) or not (e.g. the linguistic cue requires to perform a power grip and the object elicits a precision one). In the first case, the evoked response associated with the irrelevant object gets inhibited, resulting in a slowing down of the movement times. Similar findings were reported by Ellis and colleagues. (2007; see also Knight et al., 1999) in a series of four experiments. The authors used a variant of flanker task in which two objects (a target and a distractor) were displayed. Participants had to respond to the target performing either a power or a precision grip. The task differs to the classic flanker because, as the authors suggested, each object was not only associated with an arbitrary mapping rule (as in the standard task) but also it was implicitly associated with a particular grip as the result of visual affordances. The authors found a negative grasp compatibility effect when the distractor was present in the visual scene as compared to when only one object was present. More recently, a computation model was able to replicate the results of Ellis and colleagues (Caligiore et al., 2013). The authors suggested the TRoPICALS (Caligiore et al., 2010) model, taking into account the functional and architectural structure of the brain, showing that the inhibitory effect could be due to the activation of two parallel circuits that connect the prefrontal (PRF) cortex to motor areas, through the ventral stream, one excitatory and one inhibitory. Both circuits are involved in the achievement of the task when both the target-object and the distractor-object are presented. The general idea is that the PRF cortex acting with the ventral stream modulates the selection of actions on the basis of the motor goal of the agent (Caligiore et al., 2013; Ellis et al., 2007). As discussed in the first chapter, the ventral system is involved in colour processing (Gegenfurtner & Kiper, 2003; Kravitz et al., 2014). Accordingly, our results seem to fit with this model and moreover, the ventral stream mediation could be accountable for the compatibility effect revealed only with correct colour objects.

In contrast to Experiment 1, this task fails to reveal differences in performance between natural an artefact object category. A potential explanation could take into account that when we ask to participants to perform a categorization task, colour may be a salient feature that helps to discriminate between the two categories, facilitating the recognition of natural objects as they have less variety of shape and size in comparison to artefacts, eliciting a greater competition within the object recognition system for natural objects than for artefacts. Colour information may serve an important role in resolving this competition (Price & Humphreys, 1989). Scorolli and Borghi (2015) investigated this directly, comparing three different tasks with different demands (semantic categorization, manipulation evaluation task and motion evaluation task), and the role that shape and colour play in the representation of natural objects. Their results highlighted how colour can assume a different representational weight depending on the demands of the task as compared to object shape, showing the flexibility of colour as contextual information.

In our case, tasks differ between Experiment 1 and 2, but both show specific effects related to the presentation of objects in their correct colour: in Experiment 1, an overall facilitation effect for natural objects has been detected; in Experiment 2, when the reaching movement could still be corrected (SOA=10ms), the colour of the object directly affects the motor response, both for natural and artefact entities.

However, evidence for the dichotomy between the processes of planning of action (Experiment 1) and its online control (Experiment 2) is to be taken into account (Woodworth, 1889; Fitts, 1957; Keele, 1968; Jeannerod, 1988; Glover, 2004; Elliott et al., 2010). In particular, some evidence suggests that the planning phase is influenced both by visual and cognitive information of and on the target, whereas the control phase is influenced solely by the visual information like the size, the shape, the orientation of the target (Planning-Control Model, Glover, 2004). Following this evidence, our results, that are obtained in the online control of the movement, support the Planning-Control Model (Glover, 2004), outlining that the control phase can be influenced by the presence of an irrelevant object of specific shape showed in its correct colour.

Some methodological limitations related to the task can be discussed. First of all, we are aware of the lack of a baseline condition. In other words, in this experiment, the condition in which participants performed the reach-to-grasp movement towards the device without any object. However, we were interested in directly comparing the effect of the object colour on the recruitment of the motor system. For this reason and in order to simplify the experimental design, we have excluded the baseline condition. In the following experiment, aimed to verify the reliability of the task we will introduce the baseline. An additional methodological aspect in merit to further discussion is the nature of the cue. We used words explicitly denoting the size of the cylinder. One could argue that the compatibility effect is established between the representation of abstract size driven by the linguistic cue and the size of response cylinder, and not between the motor programs deputed to grasp the cylinders and the visually presented object. As discussed in paragraph 1.5.3, there are some evidence of the modulation of kinematic parameters of the grasp due to the interference of words denoting size (Gentilucci et al., 2000), but in our case, the effect of colour should not have emerged. In any case a control condition could be useful to future investigations that can be aimed to investigate reliability of the task using abstract cues (for example associating one cylinder to the # symbol and the other cylinder to the * symbol), counterbalancing the associations.

2.3.1 Experiment 3

In the second experiment, a new task has been introduced. In order to evaluate the reliability of the task and the results, we use the same task with different object categories. In this experiment, we compare the grasp compatibility effect driven by natural objects graspable with power grip (e.g. apple), with the grasp compatibility effect driven by natural dangerous objects graspable with power grip (e.g. cactus). In comparison to the previous experiment, a control condition in which no object is shown has been added. As introduced in the first chapter, some studies have investigated what happens when we need to avoid responding to the ‘’invitations’’ offered by the object. Dangerous objects represented a special case of objects in which the aversive features are directly shown (for example, the thorns of the cactus). These studies, using different tasks, reveal that we are sensitive to object aversive features (Algom, Chajut, & Lev, 2004; Anelli, Borghi, & Nicoletti, 2012; Anelli, Nicoletti, Bolzani, & Borghi, 2013; Anelli, Ranzini, Nicoletti, & Borghi, 2013), and some of them adopted reaction times as dependent measures showing slower responses with dangerous objects compared to non-dangerous objects. The slowdown of the responses could be due to two different processes. The first considers the possibility to perceive objects affordances, to plan action and block the response after having realized that the objects are dangerous. The second is a more automatic and direct process: objects affordances are immediately perceived as aversive and the motor response is inhibited adopting a freezing behaviour (Borghi & Riggio, 2015). In our case, we expected that grasp compatibility effect is absent with dangerous objects.

2.3.2 Method

2.3.2.1 Participants

Thirty participants (20 females; mean age = 24.5 ± 3.18 SD) took part in Experiment 3. All were right-handed as measured by a standard handedness inventory, had normal or corrected-to-normal vision and did not have any colour vision impairment, as assessed with the Ishihara's Test for Colour Deficiency (1974). All were naïve as to the purpose of the experiment. One participant was excluded from analysis since the experimental apparatus did not record his responses.

2.3.2.2 Ethics Statement

All participants were 18 years or older and prior to participating, they gave their informed consent, accordingly with the ethical standards of the Declaration of Helsinki.

Moreover, the experiment complied with the ethical standards of the Italian Psychological Society (AIP, see http://www.aipass.org/node/26) and Italian Board of Psychologists (see http://www.psy.it/codice_deontologico.html). As the experiment did not involve any use of pharmaceuticals or medical equipment and or clinical treatments, the approval from the Parma hospital ethics committee was deemed unnecessary.

2.3.2.3 Stimuli

Sixteen pictures of natural objects were used as stimuli. All the objects are usually grasped with power grip. Half of them were coded as dangerous objects since clearly showed spikes on their surface. We selected only one category of objects and grasp in order to reduce the complexity of the experimental design. Although only one kind of grasp was used, the experimental design allows establishing both compatible and incompatible conditions, between the linguistic cue and the size of the irrelevant object. Each picture was presented 16 times, and 64 control trials (without any picture) was added, for a total of 320 trials.

2.3.2.4 Apparatus and Procedure

Apparatus and procedure were the same of Experiment 2.

2.3.2.5 Analyses and Results

Data analyses were performed in the same way as previous experiments.

Error Rate. Participants performed 1.00% (92 trials) of incorrect grasp showing good accuracy. All participants performed less then 18 (5%) incorrect grasp (min = 0, max = 18). No other statistics will be applied since the ER is below 5%.

Lift-off times. LTs in correct trials were considered for analysis. Moreover, given the design of the experiment, we removed LTs below 100ms as anticipatory LTs (297 trials, 2.1%) and also MTs below 100ms (1 trial, 0.01%). Model did not reveal the effect of the linguistic cue (Mpiccolo = 475ms, SE = 2.6; Mgrande = 479ms, SE = 2.4).

Movements Times. The raw MTs distribution was subjected to visual inspection, showing a marked deviation from normality. MTs below and above 2.5 SD for each participant were excluded and considered outliers (186 trials, 2.09%). Moreover, MTs directed towards the precision manipulandum were overall slower (M = 355ms, SE = 1.53ms) than MTs to the power manipulandum (M = 334ms, SE = 1.54ms) as expected by Fitts' Law (1954) Since the difference between power and precision times and since we have only objects that usually are grasped with the power grip, we centred the data of each participant on the mean of the pre-specified grasp, in order to compare compatible and incompatible conditions. Finally, here, we excluded from the analysis the control condition. The control condition will be used after to check whether and how the reach-to-grasp movements were affected by the presence of the object. The centred MTs were submitted to a new LMM with Dangerousness (two levels: dangerous and non-dangerous), Compatibility (two levels: compatible and incompatible) and SOA (two levels: 10ms and 100ms) as fixed effects, as well as all the interactions. Subjects and stimuli were set as random effects. The model results are showed in Table 5, but it is important to note that it revealed the reliable fixed effect of the critical interaction among Compatibility, Dangerousness and SOA (see Figure 7).

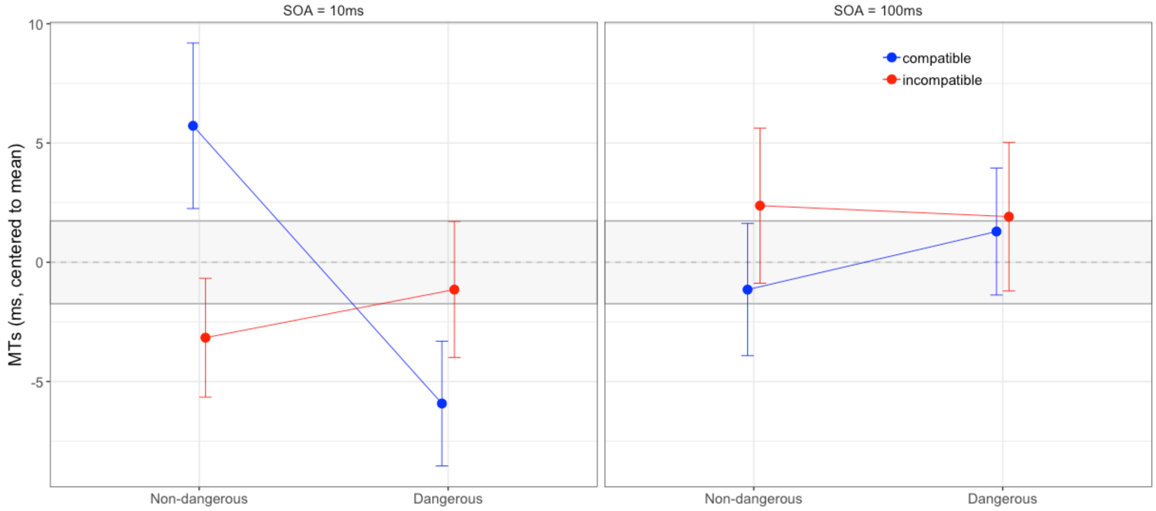

Figure 7. MTs estimated effects for Experiment 3 are shown in function of Compatibility (blue and red dots), Dangerousness and SOA factors. All error bars are 95% CI, computed with the Morey method. Intervals that do not overlap can be interpreted as evidence of a difference between conditions. In grey is showed the control condition with associated CIs. Only the Subject random intercept is showed, because, as the results of previous experiments, data showed the same trend, but CI bars overlapped.

Post-hoc analysis showed that the only compatibility effect detectable was between graspable object showed at 10ms SOA (M_{incomp} = -3.16ms, SE = 2.50; M_{comp} = 5.72ms, SE = 3.47; p-adj = 0.033). Concerning the effect of dangerous objects, post-hoc comparisons revealed a difference between the compatible conditions between dangerous and graspable objects at 10ms SOA ($M_{dangerous}$= -5.92ms, SE = 2.62; $M_{no-dangerous}$ = 5.72ms, SE = 3.47; p-adj = 0.026). Finally, no differences arise at 100ms SOA. Moreover, we tested whether the data are different from the control condition in which no objects were show, using two paired t-tests. Compatible dangerous object data and graspable compatible object data were tested independently against the control condition data. The two control conditions were collapsed because they did not show any reliable differences [$t_{(1,28)}$ = -1.74; p = 0.1; mean of the differences = -6.5, CI lower bound = -14.03, , CI upper bound = 1.15)]. Both the t-tests reveal a significant difference between the critical condition and the control condition (Dangerous: $t_{(1,28)}$ = -3.21, p = 0.023; No-dangerous: $t_{(1,28)}$ = 4.34, p = 0.012).

	Movements Times (mean centred)			
Predictors	*Estimates*	*CI*	*t*	*p*
Dangerousness	-5.92	-14.06 – 2.21	-2.81	**0.006**
Compatibility	-3.16	-11.25 – 4.93	-2.15	**0.031**
SOA	-1.15	-9.26 – 6.96	-1.66	0.097
Dangerousness:Compatibility	19.38	7.93 – 30.84	2.34	**0.019**
Dangerousness:SOA	19.81	8.36 – 31.26	2.41	**0.016**
Compatibility:SOA	18.13	6.66 – 29.60	2.12	**0.034**
Dangerousness:Compatibility:SOA	-10.84	-27.05 – 5.37	-2.00	**0.045**
Random Effects				
σ^2		7401.67		
$\tau_{00\ ss}$		0.00		
$\tau_{00\ stimuli}$		1.07		
Observations		6926		

Table 5. MTs model table. Reliable values are reported in bold

2.3.3 Discussion

Results of Experiment 3 are consistent with those of Experiment 2. Both experiments show that graspable objects automatically re-recruit the motor system, when they are displayed next to the start of a reach-to-grasp movement, leading a reversed grasp compatibility effect. Despite the differences concerning the stimuli between the two experiments, the results of Experiment 3 confirm the validity of the task and, besides, show that dangerous objects modulate in the opposite direction the motor response. Specifically, the motor response seems to be speeded up when we see a dangerous object. Anelli et al. (2013b) underlined that we tend to avoid graspable objects with dangerous affordances. The authors used a bisection line task, and results showed that participants tend to misperceive the line midpoint systematically away from the dangerous objects. In line with the idea that dangerous affordances are particularly salient for the motor system, other studies found a kind of freezing behaviour during compatibility tasks, resulting in slower reaction times when a dangerous object was presented (Algom et al., 2004; Anelli et al., 2012; Borghi & Riggio, 2015). Our results seem quite puzzling since we found faster movement times as compared to graspable objects. We suggest that our results could share a similar common process with those that generated the reversed compatibility effects found with the standard stimuli. In other words, if we directly perceive the harmfulness as well as other interactive features, than seem reasonable to speculate that not only the motor system suppresses the motor program evoked by the object, but also speed up the underway motor response (defined by the linguist cue) in order to terminate the response and turn off the potential harm linked to the dangerous object. In addition, this interpretation seems to be reinforced by the fact that the pre-specified movements conducted the participant's hand toward the dangerous object, and the participant is unable to prepare an exit strategy to avoid the contact. The only exit strategy possible is to accelerate the movement. In a seminal paper, Borghi and Riggio (2015) proposed that responses to aversive affordances reflect an automatic process, during which the motor system inhibits the motor response. The results of Experiment 3 speak in favour of Borghi and Riggio' proposal and they seem to be in keeping with findings on approach/avoidance effects, showing that we tend to be attracted by positively connoted words and to withdraw from negative ones (Chen & Barg, 2015; Freina, Baroni, Borghi, & Nicoletti, 2009; van Dantzig, Pecher, Zeelenberg, & Barsalou, 2008). Finally, the results of this experiment can also fit to the TRoPICALS model (Caligiore et al., 2010). As well established, the PFC receives information from emotional circuits (Cardinal, Parkinson, Hall, & Everitt, 2002; Etkin, Egner, & Kalisch, 2012) that may allow participants to adopt the best behavioural response to face the affordances of dangerous objects.

2.4 General discussion

Taken together results of our first three experiments show:

- Grasping affordances are modulated by different types of visual information that may reflect contextual experience and regularities in the association among object different properties;

- The modulation seems to be related to the goal and the constraints of the task, as well demonstrated by the differential results obtained in Experiments 1 and 2. The colour of the object facilitates the object recognition when categorization is required (Experiment 1), but also it can facilitate the motor system in the recruitment of the motor program usually associated with object grasp (Experiment 1 and 2);

- The motor response to visual objects is more flexible than expected. It can be adjusted online to new visual information (Experiments 2 and 3). Moreover, the adjustment is functional with respect to the interaction, with respect to avoidance of interaction with the objects.

- The results seem to speak in favour of the TRoPICALS computational model, highlighting the parallel processing of visual information in order to define and inhibit potential actions, but also the contribution of the prefrontal cortex and the ventral stream in this process.

On the basis of these points, we can speculate about how colour impact in hand-object interaction. Some studies have investigated the contribution of colour in object recognition in relation to different object categories (Algom et al., 2004; Anelli et al., 2012; Borghi & Riggio, 2015). Overall, these studies suggest an improvement in object recognition process mediated by object colour when object shape is not informative and/or when colour is highly diagnostic for the object (i.e. when the object is frequently associated to a specific colour). This is particularly true for natural objects that are, on the one hand, more similar structurally (e.g. both apple and orange have a round shape), and on the other hand, are frequently associated with a specific colour. So, colour information can be used to resolve the competition between different members of this category. This point may be particularly salient to explain the results of Experiment 1 (see also the Discussion section of the related experiment). In point of fact, it is well demonstrated that we are able to learn and store in memory regularities in the events in the world. Concerning colour and shape, some studies showed that colour and shape could also be associated together in an abstract manner. For example, Goldstone (1995) taught participants simple associations between a shape (e.g., square) and a colour (e.g., red). Later, when a coloured shape was flashed (e.g., a red square), and participants had to reproduce its colour, they distorted the colour towards the learned colour associated with the shape seen before. The author argued that perceiving the object shape, activated a simulation of its prototypical colour, which distorted the perception of the current colour. Similarly, Hansen and colleagues (2006) have shown that simulations of object's natural colour (e.g., yellow for banana) distort the achromatic perception of the object (e.g., grey banana) toward the opponent colour (e.g., a bluish banana). As discussed in the introduction there is evidence (Naor-Raz et al., 2003) that established this property is automatically represented in object that has a typical colour. With the results presented here, not only we move forward to establish that colour property is linked to the typical shape of the object, but that it can have an impact on the movement. These shape-colour associations may be activated jointly to the action parameters to interact with the object, and when one of these features is presented in an odd way (the colour in our case), the response may be blocked or suppressed, avoiding the interaction. In other words, colour may act as a sort of preliminary filter to evaluate whether or not it is favourable to start the interaction. This filter would not act as a sort of traffic light, but rather in a more sophisticated way, linked to the identity and the importance that colour has for a specific object. As discussed above, our results fit with the proposal of TRoPICALS model. Indeed, the prefrontal cortex could evaluate the correctness of visual information. Evidence suggests that the conjunction of colour and object is processed in the prefrontal cortex (Zeki & Marini, 1998). These areas (contiguous with motor areas) could send retroactive information, through the ventral stream, allowing the selection and the disambiguation of the correct object based on its typical colour. Another option is that the filter acts directly through the connection coming from koniocellular input. Almeida, Fintzi, and Mahon (2014) performing an fMRI study showed that colour information about artefacts has a direct stream to ventro-dorsal areas that are involved in sensorimotor transformations. According to these results and considerations, we believe that colour can be classified as a feature strictly linked to sensorimotor representation of the object, and thus should play a relevant role in theories of embodied cognition, moving toward a better understanding of the affordance.

To deeply investigate whether these visual features are encapsulated in semantic representation of the object, in the next chapter we move forward in the study of if and how these visual features are expressed and elaborated during language understanding.

Chapter III
Is colour an integral part of sensorimotor simulation?

Recently, it has been proposed that when specific action components are considered, affordances can be either stable or variable (Borghi & Riggio, 2015). According to these authors, stable affordances derive from perception-action patterns stored in memory, resulting from consolidated and constant (or relatively constant) experiences across different contexts of hand-object interaction. Typical stable affordances are the size, the shape, or the canonical orientation of an object. In contrast, variable affordances concern aspects that derive from temporary object characteristics (e.g., the spatial location of an object) and need constant and online updating of information in order to define the current state of the object. Given the variable nature of this information, it does not make sense to store it in memory. This distinction is particularly useful in explaining what happens during language comprehension. As discussed in Chapter I, it has been demonstrated that specific motor programs are evoked not only by visual objects but also from reading nouns of graspable objects (e.g., Marino et al., 2013). Conversely, when a task involves temporary object features during language comprehension, these do not influence the performance (Ferri et al., 2011, in experiment 2). In particular, it seems that stable affordances are primarily processed during the comprehension of language, and conversely variable affordances play a crucial role with visual objects (Borghi & Riggio, 2015). These results make sense within the embodied theories of cognition, in which language is grounded in perception, action and emotional systems (Borghi & Cangelosi, 2014; Fischer & Zwaan, 2008; Gallese, 2007; Gallese & Lakoff, 2005; Gentilucci, Stefani, & Innocenti, 2012; Glenberg & Gallese, 2012; Pulvermüller & Fadiga, 2010). The embodied approach upholds that language re-recruits mechanisms and processes of perception and motor systems, without exactly reproducing them (Anderson, 2010, 2015; Gallese & Lakoff, 2005). The recruitment would take place via mental simulation processes of experiential traces in the brain (Fischer & Zwaan, 2008; Gallese, 2007; Gallese & Lakoff, 2005; Taylor & Zwaan, 2009, Richter et al. 2009). Experiential traces are shaped through everyday interactions with objects, or with any kind of event, together with the words used to denote the event. Afterwards, when reading or hearing a word without its referent, the corresponding experiential trace gets reactivated, enabling the comprehension of the word itself (Barsalou, 2008; Glenberg & Kaschak, 2002; Richter et al., 2009). In the previous chapter, evidence of modulation of hand motor program by the colour and the dangerousness of the objects are presented. Here, we asked if and how these dangerous and colour characteristics can be expressed by language. In natural languages, the grammar category of adjectives expresses the quality of the object denoted by a noun. Therefore, adjectives can define negative or positive qualities that, in principle, could inhibit or favour the motor activation driven by nouns. Only the study of Gough et al. (2013) investigated the motor activation elicited by adjectives, performing a TMS study in which adjectives (without any nouns), expressing positive vs negative pragmatic properties, were presented. On every trial, 150ms after the adjective presentation, a single TMS pulse was applied to the participants' motor cortex, recording MEPs from two antagonistic muscles involved in avoidance and in releasing actions (the extensor communis digitorum, EC) and in approach and grasping actions (the first dorsal interosseous, FDI), respectively. Results showed that participants' MEPs of FDI were reduced (during the first block of the trials) when participants processed positive adjectives.

Conversely, the MEPs of the FDI were increased when participants read negative adjectives. The opposite pattern of results was found in the MEPs of EC. The authors suggested that the described modulations of the motor system reflect the motor experience (or the motor competence) associated with the adjectives during the acquisition of language, that later subserves the comprehension of the meaning conveyed by that adjective in a variety of contexts. However, there is a lack of experimental evidence about the contribution of adjectives on motor modulation activated by nouns.

In the present experiments, we investigated whether components of motor programs elicited by reading nouns of graspable objects can be modulated when these nouns are presented in combination with adjectives expressing disadvantageous (e.g. hot), colour (e.g. red), and shape/tactile (e.g. round) properties of the object.

We performed four experiments in order to test this possibility. In the first experiment, we tested whether the nouns selected as stimuli reveal grasp compatibility (GC) between the grasp of the denoted objects (power or precision) and the executed grasp (also, in this case, power or precision). In the second and fourth experiments, we directly compare colour and disadvantageous adjective presented in combination with nouns of graspable objects. Finally, in order to extend the results, in the third experiment, we combined nouns with adjectives related to the shape or tactile characteristics of objects (e.g. long or smooth).

3.1 Experiment 4

The fourth experiment is aimed to assess whether the nouns of graspable objects elicit components of the appropriate hand motor program associated with object interactions, as described in previous studies (see paragraph 1.5.2). Using the classic grasp compatibility task (see Experiment 1), the main expectation is the presence of the grasp compatibility effect between the evoked grasp of the object which nouns refer to and the response grip.

3.1.1 Method

3.1.1.1 Participants

Twenty-six participants (16 females; mean age in years = 20.8 ± 2.4 SD) volunteered to take part in the experiment. All participants were right-handed, as measured by a standard handedness inventory, native Italian speakers, and had normal or corrected-to-normal vision. All participants were naïve as to the purpose of the experiment.

3.1.1.2 Ethics Statement

All participants were 18 years or older and prior to participating, they gave their informed consent, accordingly with the ethical standards of the Declaration of Helsinki.

Moreover, the experiment complied with the ethical standards of the Italian Psychological Society (AIP, see http://www.aipass.org/node/26) and Italian Board of Psychologists (see http://www.psy.it/codice_deontologico.html). As the experiment did not involve any use of pharmaceuticals or medical equipment and or clinical treatments, the approval from the Parma hospital ethics committee was deemed unnecessary.

3.1.1.2 Stimuli

Thirty-two Italian nouns were selected as stimuli: eight nouns referring to natural objects graspable with a precision grip (e.g. oliva, olive), eight referring to natural objects graspable with a power grip (e.g. carota, carrot), eight referring to artefact objects graspable with a precision grip (e.g. chiodo, nail), eight referring to artefact objects graspable with a power grip (e.g. bottiglia, bottle). Each noun was presented sixteen times for a total of 512 trials. These nouns were balanced according to frequency (Laudanna et al., 1995) and number of syllables (t-tests all ps > 0.05). In addition, we used 32 pseudo-words as control stimuli, to make sure participants read the whole noun and not just the first few letters. To create pseudo-words, we scrambled the nouns and recomposed them in order to generate grammatically correct, but meaningless Italian words. We presented each pseudo-word four times (catch trials). All stimuli were displayed at the centre of the screen (1920x1280 resolution) in white colour on a black background (bold courier new, 24-point size). All nouns were submitted to a validation phase that is reported in the Appendix B.

3.1.1.2 Apparatus and Procedure

The experiment took place in a sound-attenuated and dimly illuminated room. The experimental apparatus and general procedure are the same as Experiment 1. Each trial started when the participant placed the palm of her/his right hand on the starting base. The device does not require pressure in order to detect the hand’s presence. In this way, we avoided any muscle activation of the hand or arm, reducing the possible motor interference between the action required to press a key and the response action. When participants placed their right hand on the starting base, the fixation cross (bold courier new, 30-point size) appeared at the centre of the screen. The cross remained on the screen for a variable duration between 500 and 1000 ms. Experimental stimuli replaced the fixation cross and remained on the screen until a response was provided. Participants had to categorize each noun as natural or artefact by performing either a precision or a power reach-to-grasp movement. Response grasps could be compatible or incompatible with the ones usually used to manipulate the objects denoted by the nouns. The mapping between the object category of nouns and the response on the device (power or precision cylinder) was counterbalanced across participants. In the catch trials, we presented the pseudo-words and participants did not have to carry out any reach-to-grasp movements. They were instructed to lift and reposition their right hand. For both the nouns and pseudo-words, when the participants lifted their hand, the stimuli disappeared from the screen. The experimental task started with a practice session (40 trials). After the practice trials, the experimental trials were run. The participants were tested individually, and they were instructed to find the best compromise between speed and accuracy while performing the task.

3.1.1.3 Analyses and Results

Data analyses were performed using R 3.4.4 (R Core Team, 2018), excluding from the analyses practice and catch trials. Participants' LTs (ms), MTs (ms), and error rate (ER) were recorded and analysed. The LTs were measured from stimulus onset to the lift of the hand from the starting base. The MTs were defined as the time difference between the end of the reach-to-grasp movement (the grasp of one of the two cylinders) and the hand lift from the starting position. Catch trials were a-priori excluded from analyses. Given the design of the experiments, with multiple observations for participants and stimuli, we performed the analysis on LTs and MTs using linear mixed-effects models, specifying the models with random effects for participants and stimuli, and including random slopes of each fixed effect. The LMMs was computed using Afex package. Pairwise post-hoc comparison with Tukey HSD corrections were performed on estimates effects when necessary.

Error Rate. The ER data showed that participants were accurate, performing 3.16% (421 trials) of incorrect categorizations compared to the total trials. All participants have less than 10% of error rate (min = 0.6%, max = 8.8%). We performed LMM on ERs, with Compatibility (Two levels: compatible and incompatible), Object Category (OC, two levels: natural and artefact) and Response Mapping (RM, two levels: power-to-natural and power-to-artefact) as fixed effects, Participants nested in RM were set as random effect. As showed in Table 9, the LMM revealed the only effect of Compatibility as reliable. Data showed that participants performed more incorrect classifications with incompatible trials (ER = 4.6) than compatible ones (ER = 3.5).

Lift-off Times. LTs of correct trials were considered for analysis. Thirty-seven data-points were removed from the dataset as symptomatic of anticipatory responses (<150ms). We selected only the LTs included in 2.5 standard deviations calculated for each participant (data loss: 2.58%, 333 trials). The remaining distributions of LTs were inspected to evaluate deviations from normality. As these distributions were typically characterized by positive skewness, we employed an iterative Box-Cox procedure in order to search for the meaningful lambda transformation parameter (Box & Cox, 1964; Osborne & Carolina, 2010) that best yielded a reduction of skewness across participants. We chose lambda = -1, which corresponds to the reciprocal of LTs. Visual inspection of the residuals still showed a marked deviation of the sample quantiles distribution from the theoretical quantiles. In order to assess whether these values should be considered as outliers, we used the following criterion (Leys, Ley, Klein, Bernard, & Licata, 2013):

$$\frac{abs(sample\ residuals - median\ of\ the\ residuals)}{median\ absolute\ deviation\ of\ residuals}$$

We excluded from the analysis the values that exceed three times the criterion, producing the loss of 0.97% (122 trials) of data. Distribution of the three phases of data manipulation is showed in Figure 8.

	Number of errors				**1/LTs (Transformed back)**				**1/MTs (Transformed back)**			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
OC	4.3	4.8 – 3.9	-1.1	0.28	729	723.7 – 733.8	**-2.1**	**0.04**	368	362.5 – 373.0	0.3	0.76
Compatibility	4.6	5.0 – 4.1	**-2.3**	**0.03**	739	735.0 – 742.5	**2.4**	**0.03**	370	366.6 – 373.8	1.8	0.08
RM	4.0	5.2 – 2.8	0.1	0.95	736	696.5 – 779.3	0.1	0.95	389	358.5 – 425.1	1.4	0.18
OC x Compatibility	4.1	4.5 – 3.6	-0.1	0.93	734	732.1 – 736.8	0.2	0.86	369	366.9 – 370.3	**2.0**	**0.05**
OC x RM	4.3	4.8 – 3.9	-1.2	0.24	735	732.2 – 738.3	0.6	0.54	365	361.3 – 367.7	-1.4	0.16
Compatibility x RM	3.9	4.4 – 3.5	0.5	0.61	734	730.2 – 737.6	-0.2	0.86	369	365.8 – 373.0	1.4	0.18
OC x Compatibility x RM	4.4	4.9 – 4.0	-1.7	0.10	734	731.2 – 735.9	-0.6	0.56	366	364.2 – 367.6	-1.1	0.29

Table 6. LMMs results in Experiment 1. Values in bold indicated the reliable fixed effects.

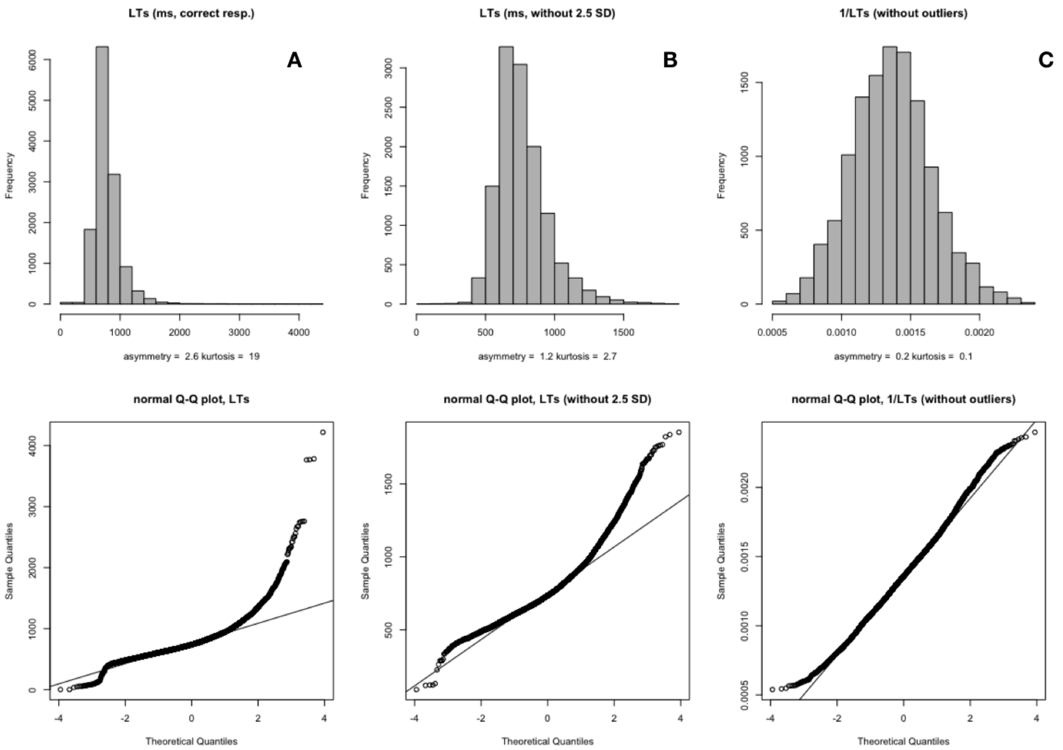

Figure 8. LTs distributions in Experiment 4. In the upper panels are reported the distributions of LTs. In the bottom panels the normal Q-Q plots associated with the distributions are showed. Below distributions graphs, the values of asymmetry and kurtosis are indicated.

LTs were submitted to LMM. The model reveals the effects of OC, with faster responses for natural (M = 728ms, SE = 3.3ms) than artefact nouns (M = 739ms, SE = 3.4ms), and for Compatibility (see Table 6). Transformed back LTs of the compatible condition was faster (M = 729, SE = 3.2ms) than for incompatible condition (M = 737ms, SE = 3.5ms), with an overall compatibility effect of 8ms.

Movement Times. We submitted MTs in a new LMM with the same structure as the previous one. Results (Table 6) show that only the interaction between OC and Compatibility is reliable. Pairwise comparisons show a significant GC effect only for artefact nouns [compatible: 361ms (SE = 3.1); incompatible: 370ms (SE = 3.1); p = 0.006], while the GC effect referring to natural nouns did not reach statistical significance (compatible: 366ms; incompatible 368ms).

3.1.2 Discussion

The results of Experiment 4 show that when we read the noun of a graspable object, the grasp response is fast when the grasp required by the object to which the noun refers to is the same than the grasp required by the task. Conversely, the mismatch between the two grasps causes a slowdown of the LTs. These results are in line with the embodied cognition view, providing further evidence that the comprehension of concrete nouns goes through the motor system (Horoufchin, Bzdok, Buccino, Borghi, & Binkofski, 2018; Marino et al., 2013; Marino, Gallese, Buccino, & Riggio, 2012). We found the GC effect both for natural and for artefact object nouns (8ms), but these effects are different in their time course. Indeed, the GC effect is also significantly reliable in the movement times for artefact nouns (9ms). Converging evidence comes from the findings of Gough et al.' TMS study (2012) in which an increment of MEP responses with artefact nouns in comparison to natural nouns were found. This difference between noun categories with regard to the GC effect may be related to the fact that artefact objects are associated not only with simple motor programs of prehension, but also with manipulation and use (Gough et al., 2012). In line with this explanation, we find that responses to natural nouns were faster than responses to artefact ones. In other words, artefact objects seem not only more effective, but also more demanding for the motor system in comparison to natural objects.

3.2 Experiment 5

In Experiment 5, the main manipulation consists in presenting the graspable object nouns together with adjectives, expressing disadvantageous (e.g. hot)[4] or colour (e.g. red) qualities of the objects denoted by nouns. As shown with visual objects (see Chapter II), both the disadvantageous and colour properties modulate the motor program elicited by the vision of objects. Similarly, when an object property is expressed in language through adjectives, this property might modify the sensorimotor simulation driven by nouns. Therefore, we expect to detect grasp compatibility effects when nouns are associated with colour adjectives, and the reduction of grasp compatibility when nouns are associated with disadvantageous adjectives. However, it is also possible that in a categorization task, the object colour is useful to discriminate between artefacts and natural objects, facilitating the response to natural objects as compared to man-made ones, as highlighted by the results of Experiment 1. In this case, the task is the same, and on the basis of evidence from Experiment 1, colour may be represented differently between artefact and natural object nouns, modulating the response mainly for natural object nouns.

3.2.1 Methods

3.2.1.1 Participants

Twenty-six new participants (16 females; mean age in years = 23.2 ± 3.3 SD) volunteered to take part in the experiment. All participants were right-handed (as measured by a standard handedness inventory (Oldfield, 1971), native Italian speakers, and had normal or corrected-to-normal vision. All participants were naïve as to the purpose of the experiment and gave their informed consent prior to participation. The experiment under the Declaration of Helsinki and the ethical standards defined previous experiments.

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[4] The disadvantageous term has been used to include other object features which are not harmful (e.g. the thorns of a cactus), but which prevent or hinder the grasp.

3.2.1.1 Stimuli, Apparatus and Procedure

We used the same nouns validated in the previous experiment. Moreover, eight different adjectives denoting a disadvantageous quality (e.g. tagliente, sharp) were selected. The noun-adjective combinations were subjected to further validation. The results are reported in the supplementary materials, but, in short, all participants indicated that the disadvantageous adjectives made the objects indicated by the nouns difficult to grasp. Moreover, all the proposed combinations were familiar, previously used and easy to imagine by participants.

After this validation, we created a second list of noun-adjective combinations using eight different adjectives denoting the appropriate colour for each object. In this way, we created two lists of nouns and adjectives (with eight objects nouns for each combination of object category and grip), with a total of 64 combinations. To be sure that participants read the nouns of the combination during the experiment, we added 32 control combinations (catch trials). Each combination consisted of one of the nouns used as stimuli and an adjective denoting a human quality (e.g. oliva emotiva, emotive olive).

The apparatus and procedure remained the same as described in the previous experiment. Each combination was presented eight times, for a total of 512 trials. In the catch trials, each control combination was presented four times, and participants had to lift up their hand without performing any reach-to-grasp movement when these stimuli were presented.

3.2.1.2 Analyses and results

Data were analysed with the same procedure as described in Experiment 4.

Error Rate. The ER data showed that participants were accurate, but less than in the previous experiment, performing 4.5% (559 trials) of incorrect categorizations. All participants had less than 15% of error rate (min = 0.8%, max = 13.7%). The LMM did not show any reliable effects.

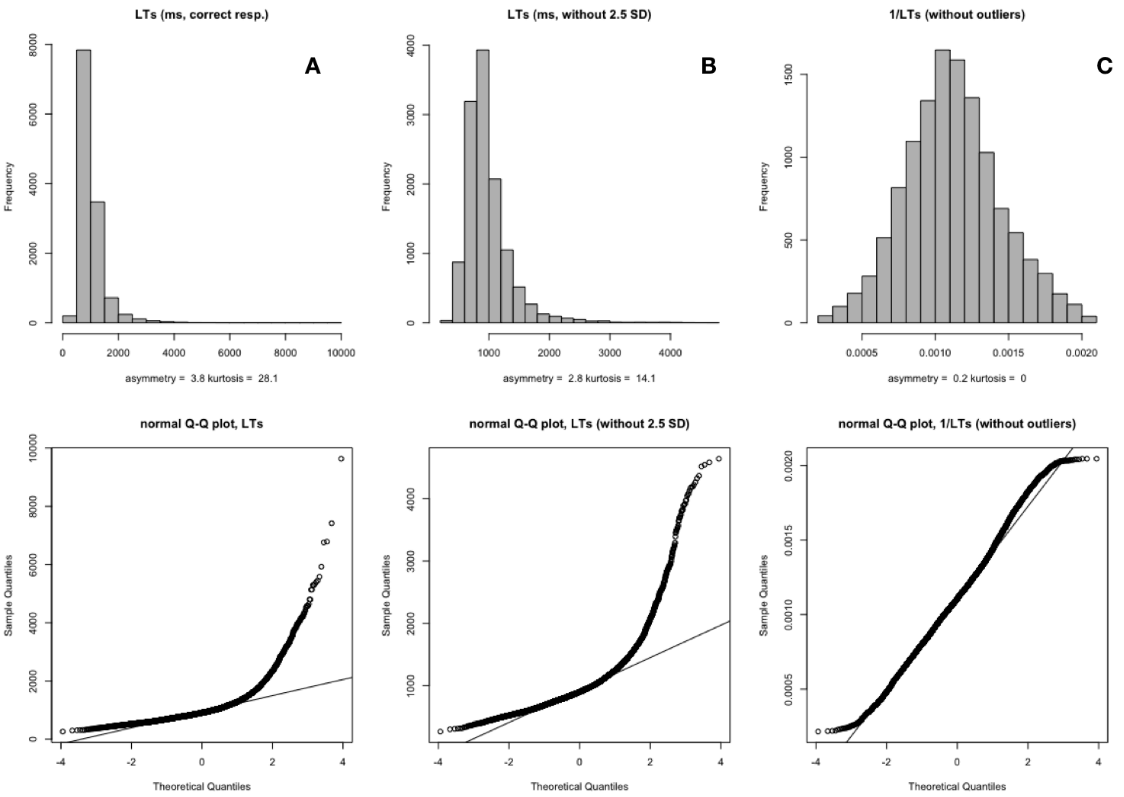


Figure 9. LTs distributions in Experiment 5. In the upper panels are reported the distributions of LTs. In the bottom panels the normal Q-Q plots associated with the distributions are showed. Below distributions graphs the values of asymmetry and kurtosis are indicated.

Lift off Times. LTs of correct trials have been considered for analysis. Forty data-points were removed from the dataset as symptomatic of anticipatory responses (<150ms). Responses above or below 2.5 standard deviations were excluded (data loss: 2.5%, 334 trials). Outliers were computed with the same criterion as in Experiment 4, producing a loss of 1% (127 trials) of data.

The LTs were submitted to a new LMM, with Compatibility, OC, Adj and RM as fixed effects, specifying the models with random effects for participants and stimuli, and including also random slopes of each fixed effect. The model reveals the reliable effect of Compatibility that become clearer considering the three-way interaction among Adj, OC, and Compatibility (see Table 8 and Figure 10).

		Disadvantageous		**Colour**	
		Mean	*SE*	*Mean*	*SE*
Artefact	**Compatible**	915	6.4	930	6.5
	Incompatible	919	5.7	931	7.7
Natural	**Compatible**	903	5.4	900	6.6
	Incompatible	909	9.0	938	8.5

Table 7. Descriptive statistics of LTs. All descriptive statistics are reported in ms.

Post-hoc comparisons revealed that the compatibility effect is generated by natural nouns when associated with colour adjectives ($p < 0.001$). A compatibility effect was found neither with artefact nouns associated with the two adjective types, nor with natural nouns associated with disadvantageous adjectives. Moreover, for natural nouns, the incompatible condition with colour adjectives was significantly slower than both compatible and incompatible conditions with disadvantageous adjectives ($ps < 0.006$). Descriptive statistics of LTs are reported in Table 7.

Movement times. The LMM performed on MTs did not show any reliable effects.

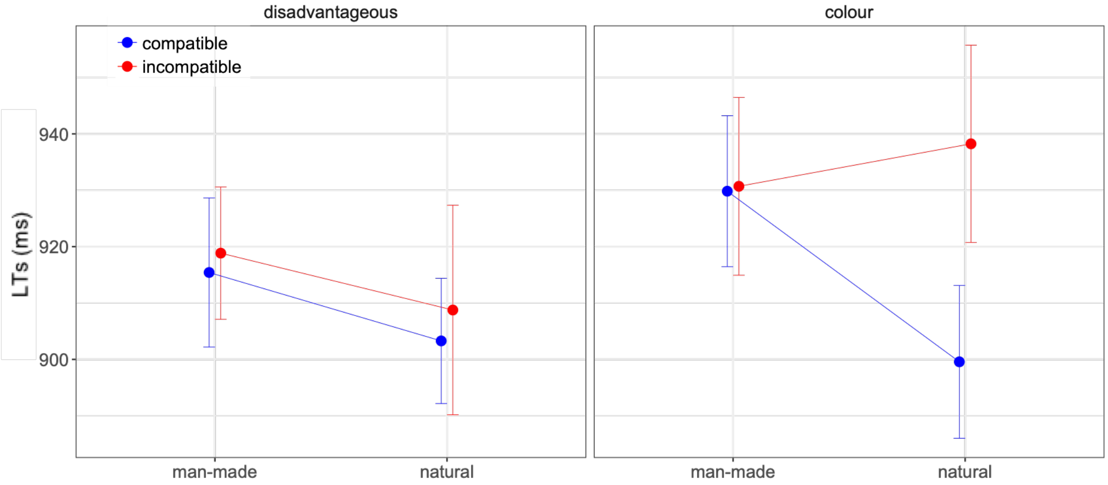


Figure 10. Results of the three-way interaction. Dots indicate the average values of transformed back LTs. Blue and red colours indicate compatible and incompatible conditions, respectively. Error Bars are 95% CI's, computed with the Morey method.

	Number of errors				1/LTs (Transformed back)				1/MTs (Transformed back)			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
OC	2.8	3.2 – 2.5	-0.8	0.44	896	907.4 – 884.6	-0.8	0.43	347	341.4 – 352.0	0.4	0.72
Adj	2.7	3.1 – 2.4	-0.3	0.77	887	897.4 – 877.2	0.8	0.43	346	342.9 – 349.0	0.2	0.87
Compatibility	3.0	3.3 – 2.6	-1.5	0.15	887	891.0 – 882.3	**2.1**	**0.04**	345	343.4 – 346.8	-0.6	0.53
RM	2.0	2.8 – 1.3	1.8	0.09	892	955.3 – 835.8	-0.1	0.99	330	311.9 – 350.9	-1.5	0.15
OC x Adj	2.6	2.9 – 2.2	0.6	0.58	892	901.7 – 881.7	-0.1	0.95	348	344.6 – 350.8	1.3	0.21
OC x Compatibility	2.7	3.1 – 2.4	-0.3	0.77	895	898.5 – 890.5	-1.6	0.12	346	344.3 – 347.4	0.2	0.82
Adj x Compatibility	2.6	2.9 – 2.2	0.6	0.54	893	897.1 – 889.5	-1.1	0.29	346	344.5 – 347.3	0.3	0.74
OC x RM	2.5	2.9 – 2.2	1.0	0.33	894	900.9 – 888.0	-1	0.35	346	342.0 – 351.0	0.3	0.75
Adj x RM	2.8	3.1 – 2.4	-0.5	0.65	891	895.3 – 886.9	0.1	0.93	345	343.1 – 345.9	-1.6	0.11
Compatibility x RM	2.8	3.1 – 2.4	-0.6	0.58	887	897.5 – 877.1	0.8	0.44	345	341.3 – 347.7	-0.7	0.46
OC x Adj x Compatibility	2.7	3.0 – 2.3	-0.0	0.98	887	890.5 – 883.1	**2.4**	**0.02**	345	343.2 – 345.9	-1.6	0.12
OC x Adj x RM	2.6	2.9 – 2.2	0.7	0.48	889	892.8 – 885.4	1.2	0.24	347	345.1 – 347.9	1.2	0.25
OC x Compatibility x RM	3.0	3.4 – 2.7	-1.8	0.07	893	903.5 – 883.2	-0.4	0.71	345	341.9 – 348.1	-0.4	0.66
Adj x Compatibility x RM	2.5	2.8 – 2.1	1.2	0.24	893	902.7 – 882.5	-0.2	0.82	345	341.5 – 347.5	-0.8	0.45
OC x Adj x Compatibility x RM	2.6	3.0 – 2.3	0.2	0.81	8923	902.8 – 882.7	-0.3	0.78	345	342.5 – 348.6	-0.1	0.92

Table 8. LMMs results in Experiment 5. Values in bold indicated the reliable fixed effects.

3.2.2 Discussion

The results of Experiment 5 show that qualities expressed by adjectives shape the motor activation driven by nouns of graspable objects, providing further evidence for language simulation processes to go beyond the single word-level (Lachmair et al., 2016). In particular, disadvantageous adjectives eliminate/reduce the GC effect as expected, both for artefacts and natural nouns. Disadvantageous adjectives may act on the motor system in a similar way to what happens in the visual domain with dangerous affordances (see also the results of Experiment 3). For example, Anelli et al. (2012), in experiment 2, comparing, in a priming task, dangerous and neutral visual objects showed that participants are slower to respond to dangerous stimuli, probably due to a blocking mechanism of motor programs. Concerning language, convergent results were also found in a TMS study by Gough et al., (2013) in which adjectives expressing either negative or positive pragmatic properties were presented in isolation. They found a reduction of MEPs in a muscle normally involved in releasing and avoidance (the extensor communis) when participants read adjectives expressing negative qualities. However, language understanding is rarely based on accessing the meaning of singular words such as adjectives. Therefore, it is important to evaluate the role of adjectives when they are associated with nouns. In this experiment, we demonstrate that adjectives conveying disadvantageous information about grasping are capable of reducing or blocking the elicitation of stable affordances driven by nouns of graspable objects, as found in Experiment 4.

In our case, the presentation of nouns of natural objects in combination with adjectives denoting their correct colour may activate a richer representation (via processing of both size and colour), driving to a more effective language simulation. The motor effect found when colour adjectives are combined with nouns of natural objects, therefore, could also be explained in terms of keeping active the motor simulation beyond the nouns, when a represented feature is expressed (Lachmair et al., 2016). This idea could also explain the absence of GC effect when colour adjective colour is associated with artefact nouns. As far as artefact objects are concerned, colour information is less useful to interact with them, since they are represented mainly in terms of manipulative features (e.g. shape or size). Therefore, for artefact object nouns, it may be possible that motor simulation decay when participants read colour adjective after the noun, leading to no difference between compatible and incompatible conditions. In other words, when a colour adjective is presented in association with an artefact noun, it is likely that the linguistic focus shifts to perceptual features that do not appear integrated into the sensorimotor representation of the object which the noun refers to, shifting the focus away from the affordances driven by the noun, thus terminating the sensorimotor simulation. On the contrary, the simulation is maintained beyond nouns when colour is associated with natural objects, as the simulation deems the colour as a stable/prototypic feature as well.

3.3 Experiment 6

Experiment 5 showed that the grasp compatibility effect with colour adjectives emerged only for natural nouns. The lack of any compatibility effects for nouns referring to artefact objects (both with colour and disadvantageous adjectives) do not allow us to establish if the quality expressed by the adjectives is integrated in the motor representation of artefact nouns. Moreover, another aspect that might have influenced these results was that some of them the disadvantageous adjectives change also their shape, not just graspability. For example, “chopped” makes the object graspable with a pinch rather than a power grip, so that the compatibility effect seems to disappear because the “incompatible” grasp is now actually more compatible with the object (e.g., a chopped carrot requires precision rather than the power grip needed for a whole carrot).

For this reason, we performed an additional experiment in which we used adjectives not changing the graspability of the object.

3.3.1 Methods

3.3.1.1 Participants

Sixteen new participants (12 females; Mean age = 24 ± 1.76 SD) volunteered to take part in the experiment. All participants were right-handed (Oldfield, 1971), native Italian speakers, and had normal or corrected-to-normal vision. On the basis of previous results, we estimated the number of participants with a previous power analysis performed with G Power 3.1. Effect size was set at 0.25, alfa and beta were set at 0.05 and 0.80, respectively. All participants were naïve as to the purpose of the experiment and gave their informed consent prior to participation. The experiment in accordance with the Declaration of Helsinki and the ethical standards defined previously.

3.3.1.2 Stimuli, Apparatus and Procedure

Apparatus and procedure were the same as the previous experiment. We used the same nouns of Experiment 1 and we combined them with 8 new adjectives expressing qualities of the objects as its shape or its tactile sensation. Trials number were the same as previous experiments. The noun-adjective combinations were subjected to a further validation. The results are reported in the supplementary materials, but all participants indicated that the adjectives do not change the chance of grasping the objects. Moreover, all combinations were familiar, previously used and easy to imagine by participants.

3.3.1.2 Analyses and results

Data were analysed with the same procedure as described in Experiments 4 and 5.

Error Rate. The ER data showed that participants were accurate performing the task with 2.65% (217 trials) of incorrect categorizations. All participants had less than 2% of error rate (min = 0.34%, max = 1.56%). The LMM (Table 4) showed the effect of OC, with more errors with natural object nouns (M = 4.2, SE = 0.40) as compared to artefact ones (M = 2.5, SE = 0.53).

Lift-off Times. LTs of correct trials have been considered for the analysis. Nine data points were removed from the dataset as symptomatic of anticipatory responses (<150ms). Responses above or below 2.5 standard deviations were excluded (data loss: 2.5%, 205 trials). Outliers were computed with the same criterion as in Experiments 4 and 5, producing a loss of 0 trial.

The LTs were submitted to a new LMM, with Compatibility, OC and RM as fixed effects, specifying the model with random effects for participants and stimuli, and including random slopes of each fixed effect. The model reveals the reliable effect of Compatibility (see Table 9), with means equal to 867 (SE = 25.6) and 881 (SE = 27.2), for compatible and incompatible conditions respectively.

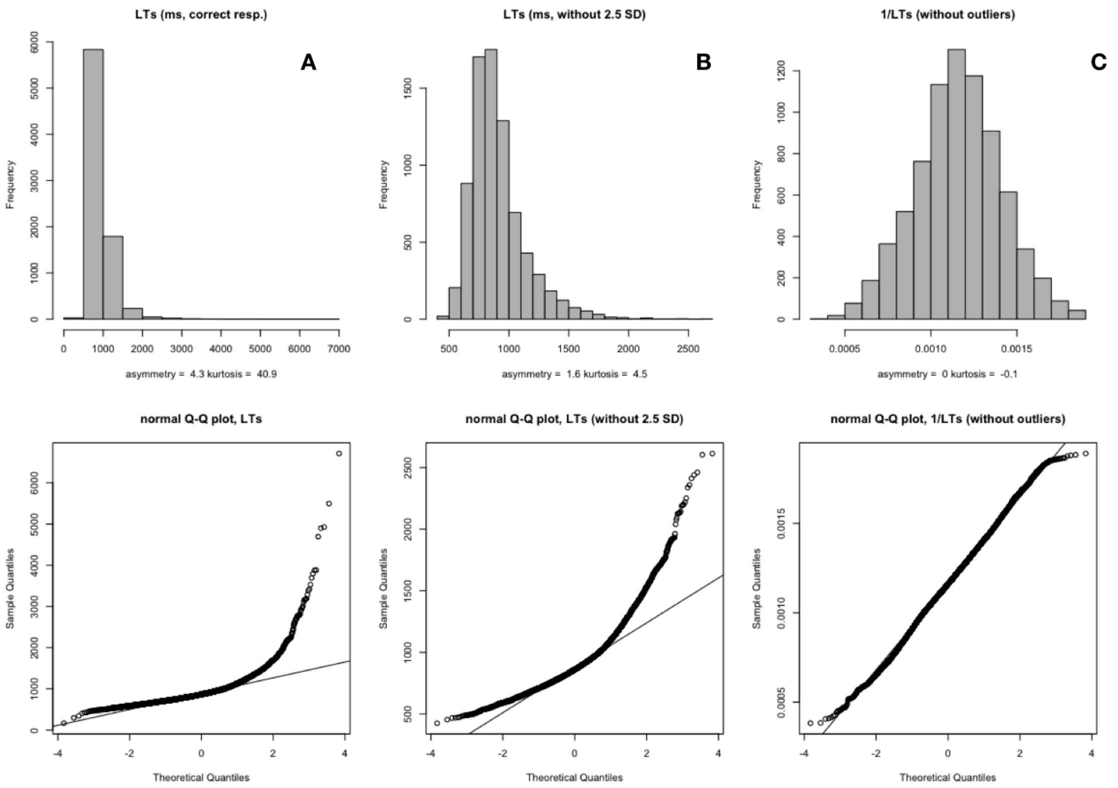


Figure 11. LTs distributions in Experiment 6. In the upper panels the distributions of LTs are reported. In the bottom panels the normal Q-Q plots associated with the distributions are showed. Below distributions graphs are indicated the values of asymmetry and kurtosis.

Movement Times. The LMM performed on MTs showed a reliable interaction effect between OC and RM. Data reveal that participants are faster when they had to grasp the cylinder compatible with the power grasp (M $_{\text{Power-to-natural- nouns}}$ = 300ms, SE = 11.2; M $_{\text{Power-to-artefact- nouns}}$ = 286ms, SE = 20.3) in comparison to the small cylinder grasp (M $_{\text{Power-to-natural- nouns}}$ = 321ms, SE = 10.4; M $_{\text{Power-to-artefact- nouns}}$ = 333, SE = 26.8), regardless of the instructions.

	Number of errors				**1/LTs (Transformed back)**				**1/MTs (Transformed back)**			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
OC	4.2	4.8 – 3.7	**-3.1**	**0.00**	866	879.7 – 852.9	-0.5	0.633	307.7	299.8 – 316.0	1.4	0.182
Compatibility	3.7	4.3 – 3.2	-1.4	0.18	857	861.4 – 851.8	**2.5**	**0.025**	299.4	294.3 – 304.7	-1.0	0.327
RM	3.6	4.5 – 2.6	-0.4	0.68	873	930.5 – 822.1	-0.4	0.714	297.0	277.7 – 319.2	-0.5	0.642
OC x Compatibility	2.9	3.4 – 2.3	1.7	0.09	865	868.8 – 861.3	-1.2	0.251	303.8	301.3 – 306.4	1.3	0.216
OC x RM	3.4	4.0 – 2.9	-0.3	0.78	859	866.9 – 850.6	1.0	0.339	287.0	281.1 – 293.1	**-4.7**	**<0.001**
Compatibility x RM	3.3	3.9 – 2.8	0.2	0.87	860	871.1 – 848.2	0.6	0.579	297.9	291.5 – 304.6	-1.2	0.225
OC x Compatibility x RM	3.2	3.7 – 2.6	0.6	0.55	862	873.1 – 850.9	0.2	0.869	300.4	295.7 – 305.3	-0.7	0.490

Table 9. LMMs results in Experiment 6. Values in bold indicated the reliable fixed effects.

3.3.2 Discussion

The results of Experiment 6 clarify and confirm the results of the previous experiment. In this case, a reliable GC effect was found, both for natural and man-made object nouns when they are associated to shape/tactile adjectives. We can interpret the current results as evidence that the motor simulation goes beyond the nouns (Lachmair et al., 2016) when the adjective expresses shape or tactile qualities, as well as the adjective refers the colour of the object.

3.4 Comparing experiments

In order to have a complete picture of the adjective modulation of GC effects, we directly compared the results of the three experiments. To compare the experiments, data collected were transformed into z-scores so to compensate the increase in variability observed in Experiment 4, 5 and6, likely due to the additional time needed to read two words instead of only one. These data were submitted to three LMMs, one for each different adjective category and comparing each one with the data from Experiment 4. All models included three fixed effects (Compatibility, OC, and Experiments) and all interactions between the effects. Participants nested in the experiments were included as random effects. Model tables are displayed below.

	Exp4 vs Exp5 (Disadvantageous Adj.)				**Exp4 vs Exp5 (Colour Adj.)**				**Exp4 vs Exp6 (Shape/Tactile Adj.)**			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
Compatibility	23.8	17.8 – 35.7	-4.7	**<0.001**	23.8	17.9 – 35.6	-4.7	**<0.001**	23.8	17.7 – 36.1	-4.6	**<0.001**
Experiment	59.5	2.9 – -3.2	-0.0	0.961	48.8	2.8 – -3.2	-0.1	0.944	77.4	2.6 – -2.8	-0.0	0.982
OC	-51.1	66.9 – -18.5	1.6	0.117	-51.3	51.2 – -17.1	1.4	0.165	-51.3	44.6 – -16.3	1.3	0.195
Compatibility x Experiment	-46.5	348.6 – -21.8	2.4	**0.016**	-350.9	46.7 – -36.9	0.9	0.357	2201.3	42.4 – -44.1	0.7	0.492
Compatibility x OC	66.2	34.3 – 920.4	-0.9	0.354	65.8	34.3 – 785.9	-0.9	0.349	65.8	33.9 – 1118.0	-0.9	0.362
Experiment x OC	54.1	14.4 – -30.9	-0.4	0.701	30.8	11.2 – -40.7	-0.8	0.415	34.8	11.2 – -31.6	-0.7	0.515
Compatibility x Experiment x OC	1471.4	39.9 – -42.2	0.6	0.530	-44.1	635.9 – -21.3	2.5	**0.012**	-154.7	60.1 – -33.8	1.3	0.203

Table 10. Model tables for all comparisons. Estimate effects, Standard Error and CIs values are reported in z-scores.

Considering disadvantageous adjectives, the LMM model selection Table (10) shows that the best model fitting our results is the model that includes the interaction between Compatibility and Experiment. As shown in Figure 12 (left panel), a reliable compatibility effect was detectable in Experiment 4 as compared to Experiment 5. CIs show that the reduction of the effect in the second experiment was due to incompatible trials as compared to compatible trials, confirming our prediction that disadvantageous adjectives reduce the compatibility effect driven by nouns of graspable objects.

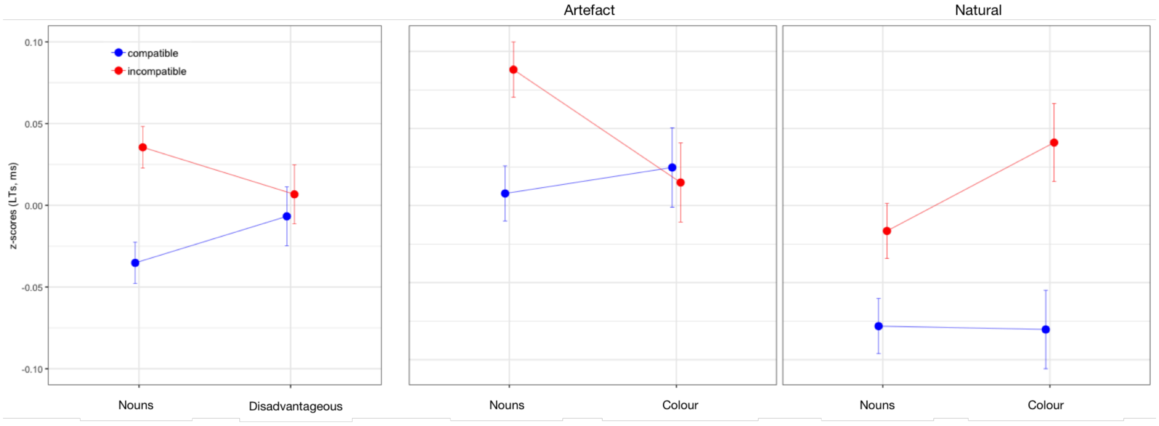


Figure 12. In the left panel are shown the results of the comparison two-way interaction between Experiment, and Compatibility when disadvantageous adjectives combination (Experiment 5) are tested against nouns showed in alone (Experiment 4). In the central and right panels are showed the results of the three-way interaction among Experiments, OC and Compatibility, in the case we tested the colour adjective combinations against the only nouns. Average values (and associated Morey's CIs) are plotted in z-scores.

Concerning colour adjectives, the model selection table shows that the best model is the one that includes the three-way interaction. As shown in Figure 12 (central and right panels), the effect of adjectives on the GC effect is different in the noun categories. Specifically, colour adjectives presented with nouns of natural objects show a difference between incompatible and compatible trials, as in Experiment 4 (Figure 12) In contrast, colour adjectives do not show the compatibility effect if presented with artefact nouns, and this is particularly noticeable in comparison to the results of Experiment 4 (Figure 13). Conversely, it seems that colour adjectives associated with natural nouns result in the strongest GC effect.

With shape-tactile adjectives, the model selection table shows that the best model is the one that includes only the fixed effect of the Compatibility, highlighting comparable GC effects to single nouns. For an overall picture of the GC effects found in the experiments see Figure 13.

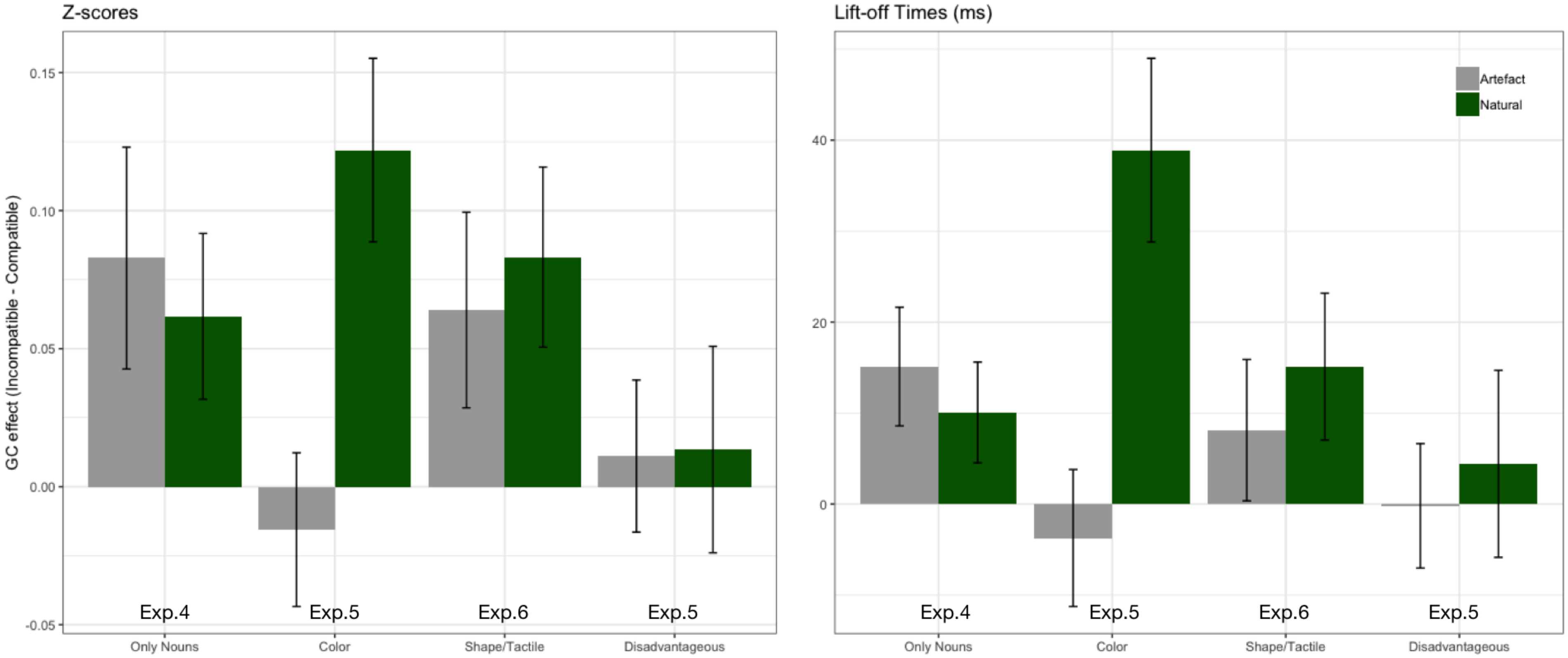


Figure 13. Summary chart of the GC effect found in Experiment 4, 5 and 6. The GC effects are presented both in z-scores (left panel) and in ms (right panel). In the X axis is indicated how the nouns are presented (e.g. only nouns or with colour adjectives). Grey and dark green colours indicate artefact or natural object nouns, respectively. Error bars are the standard error of means.

3.5 Experiment 7

This experiment is designed to conceptually replicates the results of the Experiment 5. The results of the Experiment 5, and in particular the lack of any compatible effects in artefacts nouns category, could be seen as quite puzzling and maybe the effect of type II error. Therefore, we decided to replicate the experiment in English language. Since in this case the usual reading first involves the adjective and then the noun, the combinations were presented in this order. This study will allow us to test, on the one hand, the generalization of the pragmatic role of the adjective, and, on the other hand, to highlight any differences specific to the language used.

3.5.1 Methods

3.5.1.1 Participants

Sixteen new participants (7 females; mean age = 23.8 ± 2.4 SD) are recruited at the University of Edinburgh and rewarded with a credit course. All participants were right-handed (Oldfield, 1971), with high proficiency in English, and had normal or corrected-to-normal vision. As in the previous experiment, we estimated the number of participants with a previous power analysis performed with GPower 3.1. F Effect size was set at 0.25, alfa and beta were set at 0.05 and 0.80, respectively. All participants were naïve as to the purpose of the experiment and gave their informed consent prior to participation. The experiment in accordance with the Declaration of Helsinki and has received approval from the ethics committee of the University of Edinburgh.

3.5.1.2 Stimuli, Apparatus and Procedure

We adapt the previous nouns-adjectives combinations to English with the help of a native English speaker. Some of the combinations have been changed because they cannot be adapted to the English language and replaced with other combinations (stimuli are reported in the supplementary section). Twenty-eight experimental combinations were selected and used: seven nouns referring to natural objects graspable with a precision grip (e.g. olive), seven referring to natural objects graspable with a power grip (e.g. carrot), seven referring to artefact objects graspable with a precision grip (e.g. nail), seven referring to artefact objects graspable with a power grip (e.g. bottle). Each noun was associated both with disadvantageous and colour adjectives.

To be sure that participants read both the adjective and the noun in the combination, we added 28 control combinations (catch trials). Each combination consisted of one of the nouns used as stimuli and an adjective denoting a human quality (e.g. emotive olive). The response device and procedure remained the same as described in the previous experiment. Each combination was presented eight times, for a total of experimental 448 trials. In the catch trials, each control combination was presented four times, and participants had to lift up their hand without performing any reach-to-grasp movement when these stimuli were presented.

3.5.1.3 Analyses and results

Data were analysed with the same procedure as described in the previous experiments.

Error Rate. The ER data showed that participants were accurate performing 4.38% (314 trials) of incorrect categorizations. All participants had less than 3% (12 trials) of error rate (min = 0.00 %, max = 2.68 %). The LMM only a reliable effect of Compatibility (t = -5.46, p < 0.001; Estimates = 2.09; CI =1.54 – 3.23), with more errors with incompatible trials (M = 1.75, SE = 0.72) as compared to compatible condition (M = 0.75, SE = 0.32).

Lift-off Times. LTs of correct trials have been considered for the analysis. Twelve data points were removed from the dataset as symptomatic of anticipatory responses (<150ms). Responses above or below 2.5 standard deviations were excluded (data loss: 2.65%, 190 trials). Data were visually inspected. They reveal a marked deviation from normality. LTs were transformed in 1/LTs according to Box-Cox procedure. Outliers were computed with the same criterion as in previous experiments, producing a loss of 0.86% (57 trials) of data.

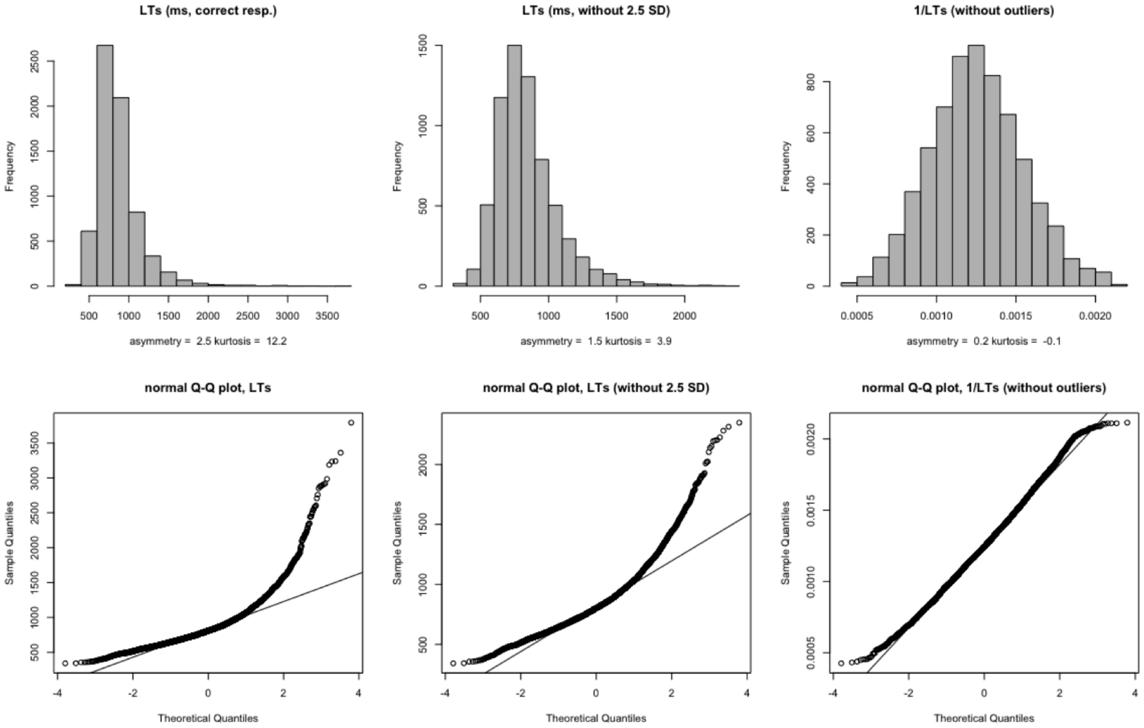


Figure 14. LTs distributions in Experiment 7. In the upper panels the distributions of LTs are reported, while in the bottom panels the normal Q-Q plots are showed. Below distributions graphs are indicated the values of asymmetry and kurtosis.

The LTs transformed were submitted to a new LMM, with Compatibility, OC, Adj and RM as fixed effects, specifying the models with random effects for participants and stimuli, and including also random slopes of each fixed effect. The model reveals the reliable interaction effects among Adj, OC, and Compatibility (see Table 13).

Post-hoc comparisons revealed that the compatibility effect is generated both by natural nouns when associated with colour adjectives (p = 0.006) and when they are associated with disadvantageous adjectives (p = 0.013).

		Disadvantageous		**Colour**	
		Mean	*SE*	*Mean*	*SE*
Artefact	Compatible	831	32.04	810	32.66
	Incompatible	824	34.26	809	33.21
	GC effect	-6		-1	
Natural	Compatible	832	29.34	785	27.28
	Incompatible	817	31.80	805	29.57
	GC effect	-15		20	

Table 11. Descriptive statistics of LTs. All descriptive statistics are reported in ms.

As shown in Figure 15 and Table 11, the two compatibility effects have opposite directions, with a reversed compatibility with disadvantageous adjectives**.** While post-hoc comparison confirms the reversed GC effect for natural object nouns (p-adj.= 0.016), for artefact nouns this do not reach the standard level of significance (p-adj. = 0.2), showing however the same trend with disadvantageous adjectives.

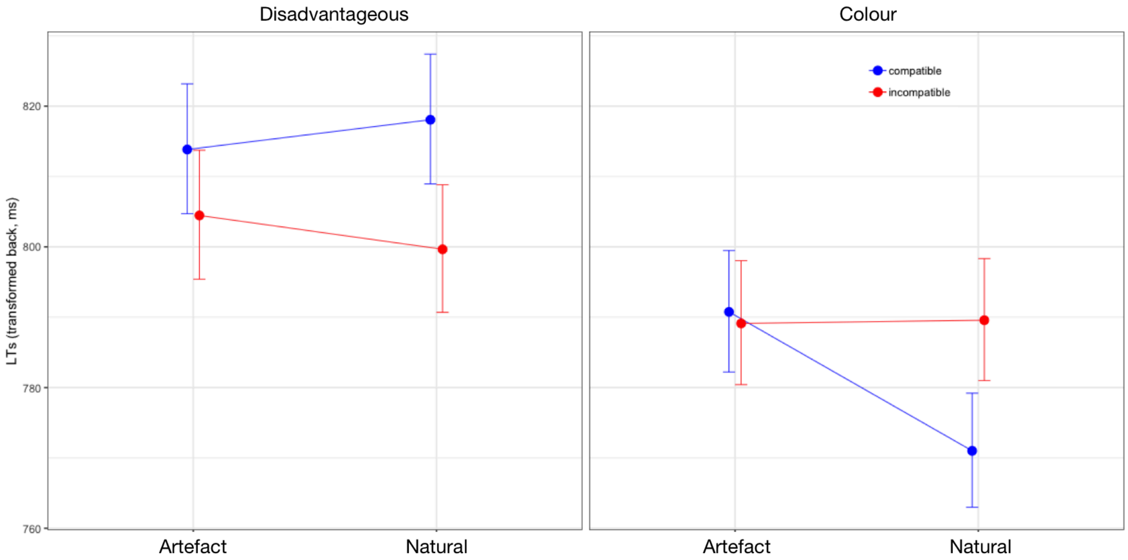


Figure 15. Results of the target three-way interaction. Dots indicate the estimated effect LTs (transformed back). Blue and red colours indicate compatible and incompatible conditions, respectively. Error Bars are 95% CI's, computed with the Morey method.

Movement Times. The LMM performed on transformed MTs showed a reliable interaction effect between OC and Compatibility and between OC and RM. These two interactions become clear in the four-way interaction among OC, Adj., RM and Compatibility (see Table 13). Data revealed different trends between the two response mappings, with a substantial continuation of what emerges in the LTs for mapping 1 (power-to-natural and precision-to-artefact). Considering the second mapping (power-to-artefact and precision-to-natural), in natural-disadvantageous combination and artefact-colour grasp compatibility effects emerge (see Figure 16 and Table 12). Even if we have no clear explanation for these effects, we will try to discuss in the next section.

		Mapping 1: Power-to-natural/Precision-to-artefact				Mapping 2: Power-to-artefact/Precision-to-natural			
		Disadvantageous		**Colour**		**Disadvantageous**		**Colour**	
		Mean	*SE*	*Mean*	*SE*	*Mean*	*SE*	*Mean*	*SE*
Artefact	Compatible	325	15.51	344	18.40	366	18.53	335	20.84
	Incompatible	332	17.75	328	16.77	370	14.72	367	14.57
	GC effect	8		-17		4		32	
Natural	Compatible	346	15.82	334	16.61	368	24.68	354	30.02
	Incompatible	355	17.29	342	15.09	383	19.10	352	21.95
	GC effect	10		7		16		-2	

Table 12. Descriptive statistics of MTs. All descriptive statistics are reported in ms.

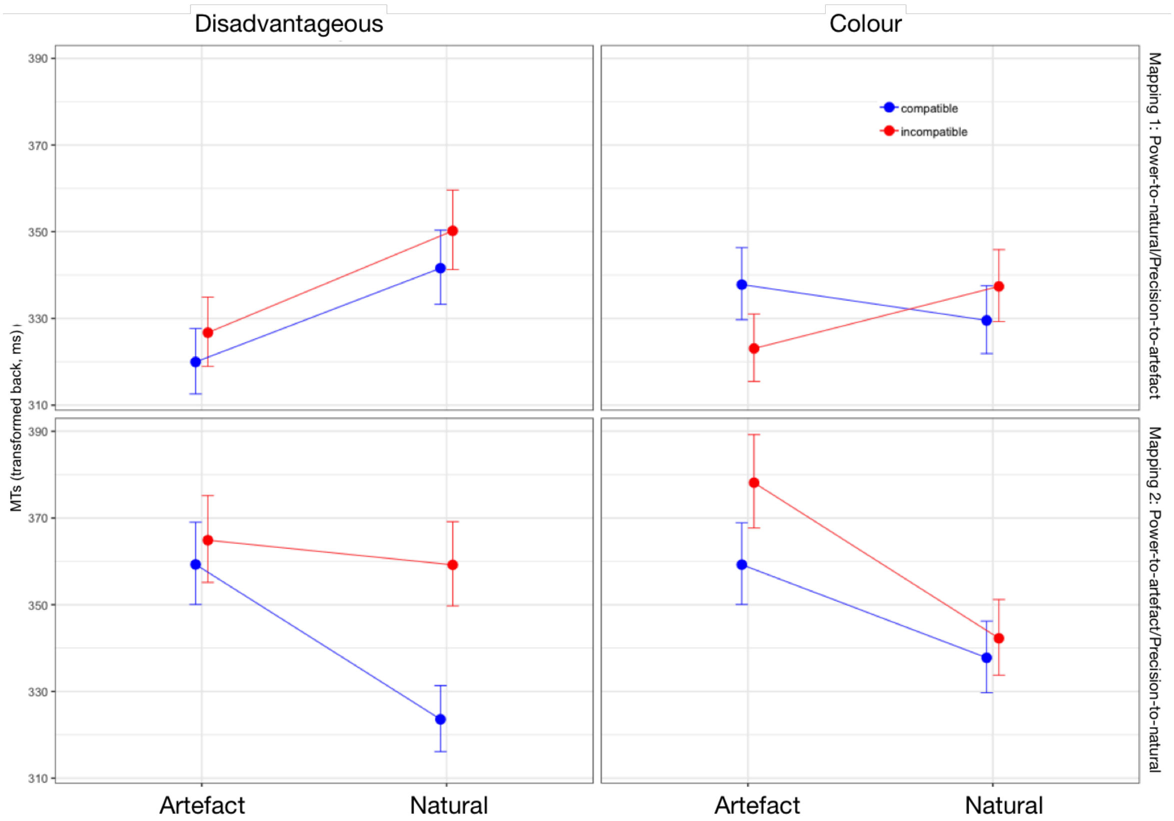


Figure 16. The graph shows the average value with associated 95% CIs of the four-way interaction of MTs.

	LTs (1/LTs transformed back, ms)				**MTs (1/MTs transformed back, ms)**			
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*
OC	808.43	829.87 – 788.07	-0.00	0.999	338.5	328.2 – 349.4	-0.4	0.680
Compatibility	812.92	820.26 – 805.70	-1.22	0.222	333.4	323.5 – 344.0	-1.4	0.180
Adjectives	790.51	810.93 – 771.09	1.72	0.091	343.7	339.3 – 348.1	1.3	0.184
RM	789.80	851.71 – 736.28	0.62	0.545	360.7	336.3 – 388.7	1.6	0.134
OC:Compatibility	812.73	823.13 – 802.60	-0.83	0.406	355.3	339.5 – 372.6	1.8	0.078
OC:Adjectives	798.02	828.00 – 770.13	0.70	0.490	349.1	342.9 – 355.6	2.7	**0.008**
Compatibility:Adjectives	804.76	814.94 – 794.83	0.71	0.479	337.9	332.0 – 343.9	-0.9	0.353
OC:RM	806.54	816.78 – 796.56	0.36	0.718	320.6	315.3 – 326.0	-6.9	**<0.001**
Comptaibility:RM	810.49	825.43 – 796.09	-0.28	0.781	340.0	334.1 – 346.2	-0.2	0.828
Adjectives:RM	800.43	810.50 – 790.60	1.56	0.120	342.3	334.9 – 350.1	0.4	0.674
Compatibility:OC:Adjectives	793.67	807.67 – 780.13	2.06	**0.039**	335.7	327.6 – 344.2	-1.2	0.241
OC:Compatibility:RM	808.83	830.29 – 788.45	-0.04	0.969	347.5	338.8 – 356.6	1.5	0.127
OC:Adjectives:RM	813.92	828.66 – 799.70	-0.75	0.452	332.6	322.7 – 343.2	-1.5	0.137
Compatibility:Adjectives:RM	806.25	827.50 – 786.06	0.20	0.839	331.5	321.7 – 341.9	-1.7	0.089
OC:Compatibility:Adjectives:RM	805.06	835.52 – 776.75	0.22	0.825	358.8	342.7 – 376.5	2.2	**0.032**

Table 13. Model seletion tables for the reuslts of Experiment 7.

3.5.2 Discussion

Results of Experiment 7 not only replicate the findings of Experiment 5, but also shed new light on the role of adjectives and the embodied simulation process. Specifically, object categories seem to have a different representation of their properties. When natural object nouns are associated with colour adjectives robust grasp compatibility effects emerge in both experiments, demonstrating that colour takes part into the sensorimotor simulation. In contrast, data highlight that when colour adjectives are associated to artefact nouns, no GC effects are evident (at least in the starting phase of the movement, see LTs section of Experiment 7). Both the absence of the effect with artefact nouns and its presence for natural nouns emerge regardless of the presentation order related to the syntactic structure of the two languages. Considering the association between colour and natural nouns, it is quite understandable why the effect can emerge (see the discussion of Experiment 5 for more details), but it is still unclear why the grasp compatibility effect disappears with artefact nouns. One possibility is that these objects are mainly represented by manipulative terms/characteristics.

Colour may shift the process from a sensorimotor representation to a more perceptual representation including characteristics not directly related to the manipulation of the object. The results of Experiment 7, however, show a GC effect during the movement phase (see panel D of Figure 16). This effect could be linked to the presentation order of the two words in the combination. In order to solve the task, participants had to read both words. In this case the adjective is presented before the noun and, when the noun referred to an artefact, its processing did not enter the conceptual node of the artefact interfering with the sensorimotor simulation. In other words, the colour of the artefacts would not be essential for the hand-object interaction and are not “automatically” represented (and recovered from memory) as it would happen with natural nouns. Therefore, when this interference tends to decay, the GC effect emerges as it happens for power grasp.

Albeit speculative, these explanations may be necessary for a general theory of embodied language and further investigations should be needed in order to directly address these hypotheses.

Concerning disadvantageous adjectives, Experiment 7 sheds light on the mechanisms occurring when negatives properties are expressed. In Borghi and Riggio (2015, see also the Discussion of Experiment 3), they argued in favour of the automatic perception of dangerous characteristics leading to a suppression of any motor program linked to the object. Our results speak again in favour for this account since in this last experiment a negative grasp compatibility effect emerged when object nouns were preceded by disadvantageous adjectives. Reading the negative properties first could suppress (or blocking) the motor information evoked by nouns delaying the compatible response. As already noted, the effect of adjectives appears to be sensitive to semantic order of the words. Considering together Experiments 5 and 7, when the nouns were presented associated to disadvantageous adjectives, a clear reversed GC effect was observed in Experiment 7 when the adjective is the first word. In contrast in Experiment 5 in which the adjective is the second word, such an effect is not significant. This suggests that the first word has greater weight than the second one in driving the sensorimotor simulation.

3.6 General Discussion

In this chapter, we investigated the sensorimotor activation driven by nouns referring to graspable objects presented in combination with adjectives, qualifying these objects in a different way.

Four experiments were carried out. In the first experiment, we tested the GC effect driven by nouns of graspable objects. Data from Experiment 4 evidenced the GC effects, as index of the fact that the comprehension of nouns of graspable objects leads to an activation of the motor system. In the second experiment, these nouns were presented associated with two adjectives categories in order to assess their role in the modulation of the GC effect. The results showed an overall reduction of the GC effect with disadvantageous adjectives, as compared to Experiment 4.

In contrast, when colour adjectives were used in linguistic combinations, a consistent GC effect was found with nouns of natural objects, but not with artefact nouns. However, in Experiment 5 in which the nouns were associated with shape-tactile adjectives, GC effects were present in both linguistic combinations. Finally, we replicated the results of disadvantageous and colour adjectives combination in a different language, in order to disentangle the syntax role in the GC effect. Therefore, our results provide evidence for a direct modulatory influence of words from the adjective grammar category on the sensorimotor activation driven by nouns, showing that the characteristics expressed by adjectives can be integrated into the motor programs elicited by nouns.

The first and, we believe, most relevant result for the thesis purposes is the presence of the motor effect with colour adjectives combined with natural objects nouns. Besides, this effect has been replicated with different linguistic stimuli and different language syntax. As well as in the first experiment with visual stimuli, this result extended the differential effect between the two categories of objects found in Experiment 1, clearly linking it to the sensorimotor simulation and not only to object recognition.

Some studies have investigated the contribution of colour in object recognition related to different object categories (e. g., Scorolli & Borghi, 2015; Therriault et al. 2009; Naor-Raz, Tarr & Kersten, 2003; Wurm et al., 1993; Price and Humphreys, 1989). As discussed, these studies suggest an improvement in object recognition when colour is frequently associated to an object or when the shape is not informative to discern between objects (e.g. orange and apple are both round and have a similar size). This is particularly evident for natural objects. So, colour information could be used to solve the competition between different members of this category (Scorolli & Borghi, 2015).

Nevertheless, colour is not only a property that can be used in the recognition process, but it gives crucial information on object status and, consequently, the possibility to interact or not with such objects. One critical example of this statement comes from studies on the genetics of colour vision. Our trichromatic vision has evolved to maximize the possibility to detect ripe fruit amongst foliage (Gegenfurtner & Rieger, 2000; Sumner & Mollon, 2000; Surridge, Osorio, & Mundy, 2003), the degree of ripeness of the fruit and, at very least, the possibility to act or not upon the object.

Concerning the simulation process, converging evidence demonstrated that colour, along other features such as shape and orientation, can be represented when we understand a sentence that implies an object with a typical colour (Berndt, Dudschig, & Kaup, 2018; Mannaert, Dijkstra, & Zwaan, 2017; Therriault et al., 2009; Zwaan & Pecher, 2012), but differently from these studies we argued in favour of a relevant role of colour on motor simulation.

Based on the results of the present studies on language, we may also consider further the representation of stable and variable affordances in language. As previously mentioned in the introduction, only stable affordances seem to be represented in language, as they are characteristics with a lower degree of variability across different contexts and, consequently, they can be stored in memory (Borghi & Riggio, 2015).

Broadly speaking, the way we interact with objects often depends on the colour they are supposed to have, that is to say, on representation and knowledge about what we know of the typical colour of an object. It seems reasonable to speculate, at this point, that colour information on natural objects can be stored in memory, and therefore reactivated when we understand the noun of a natural object. Thus, considering that colour can be included in the conceptual core of the object, it should also be considered a stable affordance at least for natural objects.

Nevertheless, a second relevant result concerns the disadvantageous adjectives. We found, for the first times, that adjectives expressing negative qualities could block a motor program related to the object. Also in this case, the results have been replicated and extended in Experiment 7**.** Critically one could argue that some disadvantageous adjectives, used both in Experiment 5 and in Experiment 7, do not convey always the same properties, changing in some cases the shape of the object and in another cases, the graspability of the object (e.g. if *smashed* adjective is associated to *plate* noun, this means that the object can still be graspable with the precision grip; conversely, if *smashed* is combined to *egg*, this means that the object is not graspable at all). It is possible that our stimuli would mask a fine-grain effect related to the wholeness, or not, of the object and consequently to the possibility of still grasping it in the right way. I believe that this fine-grain distinction is important but not critical to the purpose of this thesis, even in the light of the fact that this distinction seems not to affect the results of the previous study of Gough and collaborators (2013). However, targeted researches are needed to clarify this issue.

As previously introduced, only a study has investigated the sensorimotor simulation driven by adjectives (Gough et., 2013). Some difference can be drawn comparing their results to our results. First of all, they investigated the sensorimotor simulation presenting the adjectives in isolation. Their results primarily showed that understanding of negative properties expressed by the adjectives pass through the cerebral area of muscles involved in avoiding action. In other words, the simulation of the action seems necessary to understand these properties. Our data showed that this simulation could be not necessary since we found a blocking/freezing behaviour when adjectives expressed negative properties (for more details see the discussion of Experiment 7). An explanation of this discrepancy may be related to the fact that our sensorimotor simulation is driven by the noun presence to which adjectives refers to. In other words, our findings can be the result of an integration process in which the quality expressed by the adjective shapes the motor representation guided by nouns. This claim is supported by the results obtained in Experiment 6 and became clearer if we take into account concurrently the two different effects showed by disadvantageous and shape-tactile adjectives. Both shape-tactile and disadvantageous adjectives act similarly in both noun categories. Shape-tactile adjectives maintain or keep active the motor representation elicited by nouns as shown by the comparison with the single nouns that reveals similar magnitude of grasp compatibility effects across conditions.

Regarding the comprehension of sensorimotor simulation process during language understanding, a third step can be considered. In general terms, our results are in agreement with previous evidence showing that language simulation processes go beyond the single-word level (Fischer & Zwaan, 2008; Lachmair et al., 2016; Marino, Gallese, Buccino, & Riggio, 2012). Indeed, if language simulation is related to specific single-words such as verbs and nouns, no impact of different kind of adjectives on the compatibility effect driven by nouns should have been observed, or alternatively, the compatibility effect should be suppressed. Evidence for simulation processes beyond the word level comes from studies that found compatibility effects during action-sentence comprehension, i.e. the Action-Sentence Compatibility Effect (ACE) (Kaschak & Borreggine, 2008; Lachmair et al., 2016; Santana & De Vega, 2013; Tettamanti et al., 2005; Zwaan & Taylor, 2006) . These studies, however, showed only a general evidence of the involvement of the motor system. Therefore, it is still not entirely clear how the simulation processes can refer to single words, or the whole sentence or both (Fischer & Zwaan, 2008; Lachmair et al., 2016).

If we consider other grammatical combinations of verbs and adverbs, previous studies have shown that the adverb modulates the motor activation driven by an action verb when the adverb specifies the characteristics of the action (e.g. slowly or quickly), maintaining focus on it. Adverbs coding for different elements of the described situation, on the other hand, shifts the focus away from the described action, leading to the termination of the simulation process (linguistic focus hypothesis; Taylor & Zwaan, 2009).

From this perspective, when adjectives qualify motor characteristics of the object (as the adverb does for the action), these participate in the motor simulation specifying the action parameters on the object. This explanation fits easily to the effect here exerted by disadvantageous adjectives since they oppose the invitations/affordances of the objects denoted by nouns, but also for effects exerted by colour and by shape-tactile adjectives.

Conclusion

The central aim of this thesis was to investigate how information about the relevant properties of an object, such as what it looks like (i.e. colour), how it is grasped, as well as our avoidance response to it (i.e. dangerousness) affect the interaction with it and its representation in terms of possibility of action. In contrast to the classic (micro-) affordance studies, we focused on a particular object feature, its colour, which is not directly related to motor hand-object interaction. Colour is an object feature that is only marginally addressed in the literature, but it is one of the most relevant experiences of the world. Through seven experiments, we demonstrated that information about colour affects motor response, modulating both the selection and the execution of the movements usually associated with object grasp. Looking inside each experiment, we can outline some peculiar aspects of how colour interacts with the motor response. First of all, colour information is exploited in a flexible way by the motor system. The differential results obtained in Experiment 1 and 2 (but also in Experiments 5 and 7) support this claim. Specifically, colour information about objects can be used to facilitate the recognition of the object (Experiment 1), as well as to facilitate the recruitment of hand motor programs (Experiments 2, 5 and 7). It follows that colour information can be used in relation to the task goals.

Moreover, when we move to explore the motor behaviour elicited by the semantic representation of the object, we can outline the specificity of colour information. As clearly demonstrated by the results of Experiments 5 and 7, colour can be included in the conceptual core of natural object sensorimotor representation and not to the sensorimotor representation of the artefacts. Actually, colour is not only a property that can be typical of natural objects, but also one that provides essential information on object status and, consequently, about the possibility to interact or not with such objects. Comparing these results with those obtained with disadvantageous and shape information given by the other classes of adjectives reinforce this claim. Both classes of adjectives affect the motor response for both categories of objects, suggesting that colour information is explicitly represented and conceptually encapsulated only in the natural object category. However, it remains unclear the difference concerning the specificity of the colour effect between visual and linguistic domain. In the visual domain, a reversed GC effect arises both with artefact and natural categories of objects (see Experiment 2), when they are shown with their correct colour in comparison when they are not. In contrast, solely the natural object nouns showed the GC effect with colour adjectives. Considering the characteristics of the two domains, it is possible to speculate that when we observe an object, the motor system takes into account the whole object with all its features showed correctly (see also the paragraph 1.2.2 for similar discussion about the richness of information) in order to interact with it. However, in order to understand the meaning of the object referent, only certain stable features are reactivated, contributing to the sensorimotor simulation.

In the light of this evidence, we can consider colour as a stable affordance (at least for natural objects) seeing as it appears to be stored in memory, represented with other stable affordances and it has a clear effect on the motor system. However, it is also right that colour does not have a defined motor correlate (e.g. as the shape of the hand for the size of an object) but is frequently associated to a specific shape and size. This is particularly evident for natural objects that have less shape variability, but their typical shape appears frequently associated with a typical colour. Moreover, colour is straight different from the classical features considered as empirical signatures of affordances. It can be related to a *quality* or a status of the object (e.g., red indicates a ripe fruit in several cases, but a gradient of red colour may also indicate a hot object), making its role salient in action selection.

Considering colour as a stable affordance leads to another theoretical implication. Affordance, albeit it is considered a relational property of the object, has been investigated mainly in terms of hand-object interaction, focusing on the role of the dorsal stream in the online processing of visual features that could generate the correct motor program. Considering colour as a kind of affordance raises the issue the role of the ventral stream in coding action behaviours. Young (2006), on the basis of neuropsychological evidence raised the same issue, that is: *“whether affordances are allied exclusively to dorsal stream processing within the visual system, or whether in fact different affordances are subserved by functionally independent neural pathways”.* The author suggests that both visual streams are necessary for a proper grasping action, and that the specific role of ventral stream is to select the action based on object features and identity (for example, the function of the object). In other words, the visual information processed by the ventral stream is able to guide the actualisation of the movement through the dorsal stream (see also in the 1.5.4 paragraph for the TRoPICALS model for a similar explanation). Our evidence is in line with this point of view. While the ventral pathway seems the perfect candidate to explain the effect of colour in the visual domain, for the language experiments we should take into account also the role of ventro-dorsal subdivision that is deputed to sensorimotor transformation and, as already discussed, seems to have a generative role in the affordance effect during nouns understanding (Fischer & Zwaan, 2008; Horoufchin, Bzdok, Buccino, Borghi, & Binkofski, 2018; Marino et al., 2013), and it might be involved in the semantic effect found with colour adjectives, since stable affordances are represented. The involvement of different systems (even if they are correlated) may explain the difference emerging between natural and artefact nouns as well as the difference between vision and language domains.

Rather than considering them as segregated pathways that independently process available information, it is important to consider that these systems work in an integrated fashion, reflecting the gradient of the availability and processing of relevant information provided by the visual scene.

Taking into account the results provided in the linguistic domain, we establish, for the first time, that adjectives can shape the sensorimotor activation elicited by nouns of graspable objects. In particular, we replicated the GC effect with nouns, and we extended this result to noun-adjective combinations. In general terms, we have demonstrated the significance of the adjectives in the sensorimotor representation elicited by the nouns of graspable objects, in accord with previous evidence showing that language simulation processes go beyond the single-word level. General evidence for simulation processes beyond the word level comes from studies that found ACE (Lachmair et al., 2016; Taylor & Zwaan, 2008). Although these studies provided only a general evidence for the involvement of the motor system, with the results found with adjective-nouns combinations, we are moving forward to establish *how* it happens. As discussed previously, the modulation of the motor activation driven by an action verb when the adverb specifies the characteristics of the action, keeping the sensorimotor simulation process active. A similar mechanism may explain the adjective effect.

From this perspective, when adjectives qualify motor characteristics of the object (as the adverb does for the action), they participate in the motor simulation by specifying the parameters of the action on the object. This explanation is particularly relevant to the effect exerted here by disadvantageous adjectives, as they oppose the invitations/affordances of the objects denoted by nouns, but also for effect exerted by colour adjectives. In this latter case, colour is motorically significant for natural objects in particular, but less for artefact objects. Therefore, when a colour adjective is presented in association with a man-made noun, it is likely that the linguistic focus shifts to perceptual features that do not appear to be integrated into the sensorimotor representation of the object which the noun refers to, shifting the focus away from the affordances driven by the noun, thus terminating the sensorimotor simulation. On the contrary, the simulation is maintained beyond nouns when colour is associated with natural objects, as the simulation deems the colour as a stable feature as well.

Considering the issue of how dangerous/disadvantageous information is handled by the motor system, the results of Experiments 3 and 7 seems to speak in favour to direct processing of this kind of information. The results showed that seeing or processing dangerous object features block the compatible motor program, leading to a faster response in the case that no exit strategy can be performed (Experiment 3 with interference task) or to a slower response when the task required to start the movement after reading the disadvantageous adjectives (Experiment 7 with grasp compatibility task). In other words, it seems that our motor system is able to process the dangerousness of an object without first simulating the motor program and after inhibiting it, in line with the Borghi and Riggio's proposal (2015).

Finally, the comparison between the results obtained with Italian combinations of the noun-disadvantageous adjectives (Experiment 5) and English combination of disadvantageous adjectives and nouns (Experiment 7) provide preliminary evidence of the role of syntax in embodied language simulation. It is the first word in the combination that appears to have a greater impact in the origination on the GC effect. However, two conditions that are critical for the confirmation of this claim are absent. Specifically, the inversion of syntactic order in both languages must be performed in order to investigate the role of syntax in embodied language comprehension. Albeit this claim is not the aim of this thesis, we believe that investigating whether syntax has a role in the simulation process may be a fruitful direction for future research.

References

Algom, D., Chajut, E., & Lev, S. (2004). A Rational Look at the Emotional Stroop Phenomenon : A Generic Slowdown, Not a Stroop Effect. *Journal of Experimental Psychology: General*, *133*(3), 323–338. https://doi.org/10.1037/0096-3445.133.3.323

Almeida, J., Fintzi, A. R., & Mahon, B. Z. (2014). Tool Manipulation Knowledge is Retrieved by way of the Ventral Visual Object Processing Pathway. *Cortex*, *49*(9), 2334–2344. https://doi.org/10.1016/j.cortex.2013.05.004.Tool

Ambrosecchia, M., Marino, B. F. M., Gawryszewski, L. G., & Riggio, L. (2015). Spatial stimulus-response compatibility and affordance effects are not ruled by the same mechanisms. *Frontiers in Human Neuroscience*, *9*(May), 1–11. https://doi.org/10.3389/fnhum.2015.00283

Ambrosini, E., & Costantini, M. (2013). Handles lost in non-reachable space. *Experimental Brain Research*, *229*(2), 197–202. https://doi.org/10.1007/s00221-013-3607-0

Anderson, M. L. (2010). Neural reuse: A fundamental organizational principle of the brain. *Behavioral and Brain Sciences*, *33*(04), 245–266. https://doi.org/10.1017/S0140525X10000853

Anderson, M. L. (2015). Précis of after Phrenology: Neural Reuse and the Interactive Brain. *Behavioral and Brain Sciences*, *39*. https://doi.org/10.1017/S0140525X15000631

Anderson, S. J., Yamagishi, N., & Karavia, V. (2002). Attentional processes link perception and action. *Proceedings of the Royal Society B: Biological Sciences*, *269*(1497), 1225–1232. https://doi.org/10.1098/rspb.2002.1998

Andres, M., Finocchiaro, C., Buiatti, M., & Piazza, M. (2015). Contribution of motor representations to action verb processing. *Cognition*, *134*, 174–184. https://doi.org/10.1016/j.cognition.2014.10.004

Anelli, F., Borghi, A. M., & Nicoletti, R. (2012). Grasping the pain: Motor resonance with dangerous affordances. *Consciousness and Cognition*, *21*(4), 1627–1639. https://doi.org/10.1016/j.concog.2012.09.001

Anelli, F., Nicoletti, R., Bolzani, R., & Borghi, A. M. (2013). Keep away from danger :

dangerous objects in dynamic and static situations. *Frontiers in Human Neuroscience*, *7*(July), 1–12. https://doi.org/10.3389/fnhum.2013.00344

Anelli, F., Nicoletti, R., & Borghi, A. M. (2010). Categorization and action: What about object consistence? *Acta Psychologica*, *133*(2), 203–211. https://doi.org/10.1016/j.actpsy.2009.11.009

Anelli, F., Ranzini, M., Nicoletti, R., & Borghi, A. M. (2013). Perceiving object dangerousness: an escape from pain? *Experimental Brain Research*, *228*, 457–466. https://doi.org/10.1007/s00221-013-3577-2

Archambault, P. S., Ferrari-Toniolo, S., Caminiti, R., & Battaglia-Mayer, A. (2015). Visually-guided correction of hand reaching movements: The neurophysiological bases in the cerebral cortex. *Vision Research*, *110*(PB), 244–256. https://doi.org/10.1016/j.visres.2014.09.009

Ariga, A., Yamada, Y., & Yamani, Y. (2016). Early Visual Perception Potentiated by Object Affordances: Evidence From a Temporal Order Judgment Task. *I-Perception*, *7*(5), 1–7. https://doi.org/10.1177/2041669516666550

Azaad, S., Laham, S. M., & Shields, P. (2019). A meta-analysis of the object-based compatibility effect. *Cognition*, *190*(April), 105–127. https://doi.org/10.1016/j.cognition.2019.04.028

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*(August), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Barsalou, L. W., Pecher, D., Zeelenberg, R., Simmons, W. K., & Hamann, S. B. (2005). Multimodal Simulation in Conceptual Processing. In *Categorization inside and outside the laboratory: Essays in honor of Douglas L. Medin.* (pp. 249–270). Washington, DC, US: American Psychological Association. https://doi.org/10.1037/11156-014

Beauchamp, M. S., Haxby, J. V., Jennings, J. E., & DeYoe, E. A. (1999). An fMRI version of the farnsworth-munsell 100-hue test reveals multiple color-selective areas in human ventral occipitotemporal cortex. *Cerebral Cortex*, *9*(3), 257–263. https://doi.org/10.1093/cercor/9.3.257

Berndt, E., Dudschig, C., & Kaup, B. (2018). Green as a cbemcuru: modal as well as amodal color cues can help to solve anagrams. *Psychological Research*, *0*(0), 1–11. https://doi.org/10.1007/s00426-018-1055-y

Biederman, I. (1987). Recognition-by-Components: A Theory of Human Image Understanding. *Psychological Review*, *94*(2), 115–147. https://doi.org/10.1037/0033-295X.94.2.115

Binkofski, F., & Buxbaum, L. J. (2013). Two action systems in the human brain. *Brain and Language*, *127*(2), 222–229. https://doi.org/10.1016/j.bandl.2012.07.007

Bompas, A., & O’Regan, J. K. (2006a). Evidence for a role of action in colour perception. *Perception*, *35*(1), 65–78. https://doi.org/10.1068/p5356

Bompas, A., & O’Regan, K. J. (2006b). More evidence for sensorimotor adaptation in color perception. *Journal of Vision*, *6*(2), 145–153. https://doi.org/10.1167/6.2.5

Bonini, L., Maranesi, M., Livi, A., Fogassi, L., & Rizzolatti, G. (2014). Space-Dependent Representation of Objects and Other’s Action in Monkey Ventral Premotor Grasping Neurons. *Journal of Neuroscience*, *34*(11), 4108–4119. https://doi.org/10.1523/JNEUROSCI.4187-13.2014

Borghi, A. M., Glenberg, A. M., & Kaschak, M. P. (2004). Putting words in perspective. *Memory and Cognition*, *32*(6), 863–873. https://doi.org/10.3758/BF03196865

Borghi, A. M., & Riggio, L. (2009). Sentence comprehension and simulation of object temporary, canonical and stable affordances. *Brain Research*, *1253*, 117–128. https://doi.org/10.1016/j.brainres.2008.11.064

Borghi, A. M., & Riggio, L. (2015). Stable and variable affordances are both automatic and flexible. *Frontiers in Human Neuroscience*, *9*(March), 351. https://doi.org/10.3389/fnhum.2015.00351

Borghi, A. M., & Scorolli, C. (2009). Language comprehension and dominant hand motion simulation. *Human Movement Science*, *28*(1), 12-27.

Boulenger, V., Roy, A. C., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. A. (2006).

Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience*, *18*(10), 1607–1615. https://doi.org/10.1162/jocn.2006.18.10.1607

Box, G., & Cox, D. (1964). An analysis of transformations: Applying the Box-Cox transformation. *Journal of the Royal Satistical Society*, *Series B*(26), 211–252.

Bramão, I., Reis, A., Petersson, K. M., & Faísca, L. (2011). The role of color information on object recognition: A review and meta-analysis. *Acta Psychologica*, *138*(1), 244–253. https://doi.org/10.1016/j.actpsy.2011.06.010

Bruno, N. (2001). When does action resist visual illusions? *Trends in Cognitive Sciences*, *5*(9), 379–382. https://doi.org/10.1016/S1364-6613(00)01772-1

Bruno, N., & Battaglini, P. (2008). Integrating perception and action through cognitive neuropsychology (broadly conceived). *Cognitive Neuropsychology*, *25*(7–8), 879–890. https://doi.org/10.1080/02643290802519591

Bub, D. N., & Masson, M. E. J. (2010). Grasping beer mugs: On the dynamics of alignment effects induced by handled objects. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(2), 341–358. https://doi.org/10.1037/a0017606

Bub, D. N., Masson, M. E. J., & Cree, G. S. (2008). Evocation of functional and volumetric gestural knowledge by objects and words. *Cognition*, *106*(1), 27–58. https://doi.org/10.1016/j.cognition.2006.12.010

Bub, D. N., Masson, M. E. J., & Kumar, R. (2018). Time Course of Motor Affordances Evoked by Pictured Objects and Words, *44*(1), 53–68.

Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V., & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: A combined TMS and behavioral study. *Cognitive Brain Research*, *24*(3), 355–363. https://doi.org/10.1016/j.cogbrainres.2005.02.020

Caligiore, D., Borghi, A. M., Parisi, D., & Baldassarre, G. (2010). TRoPICALS: A Computational Embodied Neuroscience Model of Compatibility Effects. *Psychological Review*, *117*(4), 1188–1228. https://doi.org/10.1037/a0020887

Caligiore, D., Borghi, A. M., Parisi, D., Ellis, R., Cangelosi, A., & Baldassarre, G. (2013). How affordances associated with a distractor object affect compatibility effects: A study with the computational model TRoPICALS. *Psychological Research*, *77*(1), 7–19. https://doi.org/10.1007/s00426-012-0424-1

Cardinal, R. N., Parkinson, J. A., Hall, J., & Everitt, B. J. (2002). Emotion and motivation: The role of the amygdala, ventral striatum, and prefrontal cortex. *Neuroscience and Biobehavioral Reviews*, *26*(3), 321–352. https://doi.org/10.1016/S0149-7634(02)00007-6

Cattaneo, Z., Devlin, J. T., Salvini, F., Vecchi, T., & Silvanto, J. (2010). The causal role of category-specific neuronal representations in the left ventral premotor cortex (PMv) in semantic processing. *Neuroimage*, *49*(3), 2728–2734.

Chao, L. L., & Martin, a. (1999). Cortical regions associated with perceiving, naming, and knowing about colors. *Journal of Cognitive Neuroscience*, *11*, 25–35. https://doi.org/10.1162/089892999563229

Chatterjee, A. (2011). Disembodying cognition. *Language and Cognition*, *2*(1), 79–116. https://doi.org/10.1016/j.cortex.2009.08.003.Predictive

Chieffi, S., Ricci, M., & Carlomagno, S. (2001). Influence of visual distractors on movement trajectory. *Cortex*, *37*(3), 389–405. https://doi.org/10.1016/S0010-9452(08)70580-X

Cho, D T, & Proctor, R. W. (2010). The object-based Simon effect: grasping affordance or relative location of the graspable part? *Journal of Experimental Psychology. Human Perception and Performance*, *36*(4), 853–861. https://doi.org/10.1037/a0019328

Cho, D T, & Proctor, R. W. (2011). Correspondence effects for objects with opposing left and right protrusions. *Journal of Experimental Psychology : Human Perception and Performance*, *37*(3), 737–749. https://doi.org/10.1037/a0021934

Cho, D T, & Proctor, R. W. (2013). Object-based correspondence effects for action-relevant and surface-property judgments with keypress responses: Evidence for a basis in spatial coding. *Psychological Research*, *77*(5), 618–636. https://doi.org/10.1007/s00426-012-0458-4

Cisek, P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *362*(1485), 1585–1599. https://doi.org/10.1098/rstb.2007.2054

Clarke, S., Walsh, V., Schoppig, A., Assal, G., & Cowey, A. (1998). Colour constancy impairments in patients with lesions of the prestriate cortex. *Experimental Brain Research*, *123*(1–2), 154–158. https://doi.org/10.1007/s002210050556

Costantini, M., Ambrosini, E., Scorolli, C., & Borghi, A. M. (2011). When objects are close to me: Affordances in the peripersonal space. *Psychonomic Bulletin & Review*, *18*(2), 302–308. https://doi.org/10.3758/s13423-011-0054-4

Costantini, M., Ambrosini, E., Tieri, G., Sinigaglia, C., & Committeri, G. (2010). Where does an object trigger an action? An investigation about affordances in space. *Experimental Brain Research*, *207*(1–2), 95–103. https://doi.org/10.1007/s00221-010-2435-8

Creem-Regehr, S. H., & Lee, J. N. (2005). Neural representations of graspable objects: Are tools special? *Cognitive Brain Research*, *22*(3), 457–469. https://doi.org/10.1016/j.cogbrainres.2004.10.006

Dalla Volta, R., Gianelli, C., Campione, G. C., & Gentilucci, M. (2009). Action word understanding and overt motor behavior. *Experimental Brain Research*, *196*(3), 403–412. https://doi.org/10.1007/s00221-009-1864-8

De’Sperati, C., & Stucchi, N. (1997). Recognizing the motion of a graspable object is guided by. *NeuroReport*, *8*(12), 2761–2765.

De’Sperati, C., & Stucchi, N. (2000). Motor imagery and visual event recognition. *Experimental Brain Research*, *133*(2), 273–278. https://doi.org/10.1007/s002210000408

De Stefani, E., Innocenti, A., Bernardi, N. F., Campione, G. C., & Gentilucci, M. (2012). The bottle and the glass say to me: ‘Pour!’ *Experimental Brain Research*, *218*(4), 539–549. https://doi.org/10.1007/s00221-012-3047-2

De Stefani, E., Innocenti, A., De Marco, D., Busiello, M., Ferri, F., Costantini, M., & Gentilucci, M. (2014). The spatial alignment effect in near and far space: A kinematic study. *Experimental Brain Research*, *232*(7), 2431–2438. https://doi.org/10.1007/s00221-014-3943-8

De Vega, M., Robertson, D. A., Glenberg, A. M., Kaschak, M. P., & Rinck, M. (2004). On doing two things at once: Temporal constraints on actions in language comprehension. *Memory and Cognition*, *32*(7), 1033–1043.

https://doi.org/10.3758/BF03196879

Derbyshire, N., Ellis, R., & Tucker, M. (2006). The potentiation of two components of the reach-to-grasp action during object categorisation in visual memory. *Acta Psychologica*, *122*(1), 74–98. https://doi.org/10.1016/j.actpsy.2005.10.004

Desimone, R., & Schein, S. J. (1987). Visual properties of neurons in area V4 of the macaque: sensitivity to stimulus form. *Journal of Neurophysiology*, *57*(3), 835 LP – 868. Retrieved from http://jn.physiology.org/content/57/3/835.abstract

Di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: a neurophysiological study. *Experimental Brain Research*, *91*(1), 176–180.

Elliot, A. J. (2015). Color and psychological functioning : a review of theoretical and empirical work, *6*(April), 1–8. https://doi.org/10.3389/fpsyg.2015.00368

Elliott, D., Hansen, S., Grierson, L. E., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: two components but multiple processes. *Psychological bulletin*, *136*(6), 1023.

Ellis, R., & Tucker, M. (2000). Micro-affordance: The potentiation of components of action by seen objects. *British Journal of Psychology*, *91*(4), 451–471. https://doi.org/10.1348/000712600161934

Ellis, R., Tucker, M., Symes, E., & Vainio, L. (2007). Does Selecting One Visual Object From Several Require Inhibition of the Actions Associated With Nonselected Objects? *Journal of Experimental Psychology: Human Perception and Performance*, *33*(3), 670–691. https://doi.org/10.1037/0096-1523.33.3.670

Erlhagen, W., & Schöner, G. (2002). Dynamic field theory of movement preparation. *Psychological Review*, *109*(3), 545–572. https://doi.org/10.1037/0033-295X.109.3.545

Etkin, A., Egner, T., & Kalisch, R. (2012). Emotional processing in anterior cingulate and medial prefrontal cortex. *Trends in Cognitive Sciences*, *15*(2), 85–93. https://doi.org/10.1016/j.tics.2010.11.004.Emotional

Ferrari, P. F., Gallese, V., Rizzolatti, G., & Fogassi, L. (2003). Mirror neurons responding to the observation of ingestive and communicative mouth actions in the monkey ventral premotor cortex. *European Journal of Neuroscience*, *17*(8), 1703–1714. https://doi.org/10.1046/j.1460-9568.2003.02601.x

Ferri, F., Riggio, L., Gallese, V., & Costantini, M. (2011). Objects and their nouns in peripersonal space. *Neuropsychologia*, *49*(13), 3519–3524. https://doi.org/10.1016/j.neuropsychologia.2011.09.001

Fine, I., MacLeod, D., & Boynton, G. M. (2002). Surface segmentation based on the luminance and color statistics of natural scenes. *Journal of Vision*, *2*(10), 1283–1291. https://doi.org/10.1167/2.10.66

Fischer, M. H., & Adam, J. J. (2001). Distractor effects on pointing: The role of spatial layout. *Experimental Brain Research*, *137*(1), 507–513. https://doi.org/10.1007/s002210000596

Fischer, M. H., & Dahl, C. D. (2007). The time course of visuo-motor affordances. *Experimental Brain Research*, *176*(3), 519–524. https://doi.org/10.1007/s00221-006-0781-3

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *Quarterly Journal of Experimental Psychology*, *61*(6), 825–850. https://doi.org/10.1080/17470210701623605

Fitts, P. M. (1954). the Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology*, *47*(6).

Fodor, J. A. (1975). *The language of thought* (Vol. 5). Harvard university press.

Fogassi, L., Gallese, V., Buccino, G., Craighero, L., Fadiga, L., & Rizzolatti, G. (2001). Cortical mechanism for the visual guidance of hand grasping movements in the monkey: A reversible inactivation study. *Brain*, *124*(Pt 3), 571–586. https://doi.org/10.1093/brain/124.3.571

Fuster, J. M. (2001). The prefrontal cortex - An update: Time is of the essence. *Neuron*, *30*(2), 319–333. https://doi.org/10.1016/S0896-6273(01)00285-9

Gallese, V. (2007). Before and below ‘theory of mind’: embodied simulation and the neural correlates of social cognition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(February), 659–669. https://doi.org/10.1098/rstb.2006.2002

Gallese, V. (2008). Mirror neurons and the social nature of language: The neural exploitation hypothesis. *Social Neuroscience*, *3*(3–4), 317–333. https://doi.org/10.1080/17470910701563608

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain*, *119*(2), 593–609.

Gallese, V., & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*, *22*(3–4), 455–479. https://doi.org/10.1080/02643290442000310

Gallese, V., Murata, A., Kaseda, M., Niki, N., & Sakata, H. (1994). Deficit of hand preshaping after muscimol injection in monkey parietal cortex. *Neuroreport*, *5*, 1525–1529.

Gangitano, M., Daprati, E., & Gentilucci, M. (1998). Visual distractors differentially interfere with the reaching and grasping components of prehension movements. *Experimental Brain Research*, *122*(4), 441–452. https://doi.org/10.1007/s002210050532

Gegenfurtner, K. R., & Kiper, D. C. (2003). Color Vision. *Annual Review of Neuroscience*, *26*(1), 181–206. https://doi.org/10.1146/annurev.neuro.26.041002.131116

Gegenfurtner, K. R., Kiper, D. C., & Levitt, J. B. (1997). Functional Properties of Neurons in Macaque Area V3. *Journal of Neurophysiology Published*, *77*(4), 1906–1923.

Gentilucci, M, Benuzzi, F., Bertolani, L., Daprati, E., & Gangitano, M. (2000). Language and motor control. *Experimental Brain Research*, *133*, 468–490. https://doi.org/10.1007/s002210000431

Gentilucci, M.. (2003). Object familiarity affects finger shaping during grasping of fruit stalks. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *149*(3), 395–400. https://doi.org/10.1007/s00221-003-1370-3

Gerlach, C. (2001). Structural similarity causes different category-effects depending on task characteristics. *Neuropsychologia*, *39*(9), 895–900. https://doi.org/10.1016/S0028-3932(01)00031-8

Gibson, J. (1986). The Ecological Approach to Visual Perception. *The Journal of the Society of Architectural Historians*, *39*(2), 332. https://doi.org/10.2307/989638

Gibson, J. J. (1966). A Theory of Direct Visual Perception. In *Vision and Mind*. https://doi.org/10.7551/mitpress/7111.003.0007

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. *Lawrence Erlbaum, Hillsdale* (Vol. 40). https://doi.org/10.2307/989638

Girardi, G., Lindemann, O., & Bekkering, H. (2010). Context Effects on the Processing of Action-Relevant Object Features, *36*(2), 330–340. https://doi.org/10.1037/a0017180

Glenberg, A. M., & Gallese, V. (2012). Action-based language: A theory of language acquisition, comprehension, and production. *Cortex*, *48*(7), 905–922. https://doi.org/10.1016/j.cortex.2011.04.010

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*(3), 558–565.

Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology*, *61*(6), 905–919. https://doi.org/10.1080/17470210701625550

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and brain sciences*, *27*(1), 3-24.

Glover, S., Rosenbaum, D. A., Graham, J., & Dixon, P. (2004). Grasping the meaning of words. *Experimental Brain Research*, *154*(1), 103–108. https://doi.org/10.1007/s00221-003-1659-2

Goldstone, R. L. (1995). Effect of categorization on color perception. *Psychological Science*, *6*(5), 298–304.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences*, *15*(1), 1992.

Gough, P. M., Campione, G. C., & Buccino, G. (2013). Fine tuned modulation of the motor system by adjectives expressing positive and negative properties. *Brain and Language*, *125*(1), 54–59. https://doi.org/10.1016/j.bandl.2013.01.012

Gough, P. M-, Riggio, L., Chersi, F., Sato, M., Fogassi, L., & Buccino, G. (2012). Nouns referring to tools and natural objects differentially modulate the motor system.

Neuropsychologia, *50*(1), 19–25. https://doi.org/10.1016/j.neuropsychologia.2011.10.017

Grafton, S. T., Fadiga, L., Arbib, M. A., & Rizzolatti, G. (1997). Premotor Cortex Activation during Observation and Naming of Familiar Tools. *NeuroImage*, *6*(4), 231–236. https://doi.org/10.1006/nimg.1997.0293

Grèzes, J., Tucker, M., Armony, J., Ellis, R., & Passingham, R. E. (2003). Objects automatically potentiate action: An fMRI study of implicit processing. *European Journal of Neuroscience*, *17*(12), 2735–2740. https://doi.org/10.1046/j.1460-9568.2003.02695.x

Grill-Spector, K., & Malach, R. (2004). the Human Visual Cortex. *Annual Review of Neuroscience*, *27*(1), 649–677. https://doi.org/10.1146/annurev.neuro.27.070203.144220

Gross, C. G., Rocha-Miranda, C. E., & Bender, D. B. (1972). Visual properties of neurons in inferotemporal cortex of the Macaque. *Journal of Neurophysiology*, *35*(1), 96 LP – 111. Retrieved from http://jn.physiology.org/content/35/1/96.abstract

Hansen, T., Olkkonen, M., Walter, S., & Gegenfurtner, K. R. (2006). Memory modulates color appearance. *Nature Neuroscience*, *9*(11), 1367–1368. https://doi.org/10.1038/nn1794

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic Representation of Action Words in Human Motor and Premotor Cortex. *Neuron*, *41*(2), 301–307. https://doi.org/10.1016/S0896-6273(03)00838-9

Haxby, J. V., Grady, C. L., Horwitz, B., Ungerleider, L. G., Mishkin, M., Carson, R. E., … Rapoport, S. I. (1991). Dissociation of object and spatial visual processing pathways in human extrastriate cortex. *Proceedings of the National Academy of Sciences*, *88*(5), 1621–1625. https://doi.org/10.1073/pnas.88.5.1621

Horoufchin, H., Bzdok, D., Buccino, G., Borghi, A. M., & Binkofski, F. (2018). Action and object words are differentially anchored in the sensory motor system - A perspective on cognitive embodiment. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-24475-z

Howard, R. J., Ffytche, D. H., Barnes, J., McKeefry, D., Ha, Y., Woodruff, P. W., … Brammer,

M. (1998). The functional anatomy of imagining and perceiving colour. *NeuroReport*, *9*(6), 1019–1023. https://doi.org/10.1097/00001756-199804200-00012

Iani, C., Baroni, G., Pellicano, A., & Nicoletti, R. (2011). On the relationship between affordance and Simon effects: Are the effects really independent? *Journal of Cognitive Psychology*, *23*(1), 121–131. https://doi.org/10.1080/20445911.2011.467251

Ishihara, S. (1974). Tests for colour-blindness: 38 plates edition. In Kanehara Shuppan. (Ed.).

Janyan, A., & Slavcheva, G. V. (2012). When left feels right: Asymmetry in the affordance effect. *Cognitive Processing*, *13*(1 SUPPL), 199–202. https://doi.org/10.1007/s10339-012-0450-3

Jeannerod, M. (1988). *The neural and behavioural organization of goal-directed movements*. Clarendon Press/Oxford University Press.

Jeannerod, M., Arbib, M. A., Rizzolatti, G., & Sakata, H. (1995). Grasping objets: The cortical mechanisms of visuomotor transformation. *Trends in Neurosciences*, *18*(7), 314–320.

Kaschak, M. P., & Borreggine, K. L. (2008). Temporal dynamics of the action-sentence compatibility effect. *Quarterly Journal of Experimental Psychology*, *61*(6), 883–895. https://doi.org/10.1080/17470210701623852

Keele, S. W. (1968). Movement control in skilled motor performance. Psychological bulletin, 70(61), 387.

Kellenbach, M. L., Brett, M., & Patterson, K. (2003). Actions Speak Louder Than Functions: The Importance of Manipulability and Action in Tool Representation. *Journal of Cognitive Neuroscience*, *15*(1), 30–46. https://doi.org/10.1162/089892903321107800

Kemmerer, D. (2015). Are the motor features of verb meanings represented in the precentral motor cortices? Yes, but within the context of a flexible, multilevel architecture for conceptual knowledge. *Psychonomic Bulletin and Review*, *22*(4), 1068–1075. https://doi.org/10.3758/s13423-014-0784-1

Kiefer, M., & Pulvermüller, F. (2012). Conceptual representations in mind and brain:

Theoretical developments, current evidence and future directions. *Cortex*, *48*(7), 805–825. https://doi.org/10.1016/j.cortex.2011.04.006

Knight, R. T., Richard Staines, W., Swick, D., & Chao, L. L. (1999). Prefrontal cortex regulates inhibition and excitation in distributed neural networks. *Acta Psychologica*, *101*(2–3), 159–178. https://doi.org/10.1016/S0001-6918(99)00004-9

Koffka, K. (1935). *PRINCIPLES OF GESTALT PSYCHOLOGY*. *Principles of Gestalt Psychology* (Harcourt B). New York. https://doi.org/10.1037/h0052629

Kohler, E., Keysers, C., Umilta, M. A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing sounds, understanding actions: Action representation in mirror neurons. *Science*, *297*(5582), 846–848. https://doi.org/10.1126/science.1070311

Komatsu, H, & Ideura, Y. (1993). Relationships between color, shape, and pattern selectivities of neurons in the inferior temporal cortex of the monkey. *Journal of Neurophysiology*, *70*(2), 677 LP – 694. Retrieved from http://jn.physiology.org/content/70/2/677.abstract

Komatsu, Hidehiko, Ideura, Y., Kaji, S., & Yamane, S. (1992). Color Selectivity of Neurons in the Inferior Temporal Cortex of the Awake Macaque Monkey. *The Journal of Neuroscience*, *12*(2), 408–424. Retrieved from http://www.cnbc.cmu.edu/~tai/readings/color/komatsu.pdf

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional Overlap: Cognitive Basis for Stimulus-Response Compatibility-A Model and Taxonomy. *Psychological Review*, *97*(2), 253–270. https://doi.org/10.1037/0033-295X.97.2.253

Kravitz, D. J., Saleem, K. S., Baker, C. I., Ungerleider, L. G., & Mishkin, M. (2014). the Processing of Object Quality. *Trends in Cognitive Sciences*, *17*(1), 26–49. https://doi.org/10.1016/j.tics.2012.10.011.The

Lachmair, M., de la Vega, C. D. I., & Kaup, B. (2016). Constructing meaning for up and down situated sentences : Is a sentence more than the sum of its words ? *Language and Cognition*, *8*, 604–628. https://doi.org/10.1017/langcog.2015.11

Laws, K. R., & Hunter, M. Z. (2006). The impact of colour, spatial resolution, and presentation speed on category naming. *Brain and Cognition*, *62*(2), 89–97. https://doi.org/10.1016/j.bandc.2006.03.002

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology*, *49*(4), 764–766. https://doi.org/10.1016/j.jesp.2013.03.013

Luce, R. D. (1986). Response times: Their role in inferring elementary mental organization (No. 8). Oxford University Press on Demand.

Luppino, G., Murata, A., Govoni, P., & Matelli, M. (1999). Largely segregated parietofrontal connections linking rostral intraparietal cortex (areas AIP and VIP) and the ventral premotor cortex (areas F5 and F4). *Experimental Brain Research*, *128*(1–2), 181–187. https://doi.org/10.1007/s002210050833

Mahon, B. Z., & Caramazza, A. (2005). The orchestration of the sensory-motor systems: Clues from neuropsychology. *Cognitive Neuropsychology*, *22*(3–4), 480–494. https://doi.org/10.1080/02643290442000446

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology Paris*, *102*(1–3), 59–70. https://doi.org/10.1016/j.jphysparis.2008.03.004

Makris, S., Hadar, A. A., & Yarrow, K. (2011). Viewing objects and planning actions: On the potentiation of grasping behaviours by visual objects. *Brain and Cognition*, *77*(2), 257–264. https://doi.org/10.1016/j.bandc.2011.08.002

Makris, S., Hadar, A. a, & Yarrow, K. (2013). Are object affordances fully automatic? A case of covert attention. *Behavioral Neuroscience*, *127*(5), 797–802. https://doi.org/10.1037/a0033946

Mannaert, L. N. H., Dijkstra, K., & Zwaan, R. A. (2017). Is color an integral part of a rich mental simulation ? *Memory & Cognition*, *2017*(April), 974–982. https://doi.org/10.3758/s13421-017-0708-1

Marino, B. F. M., Borghi, A. M., Buccino, G., & Riggio, L. (2017). Chained activation of the motor system during language understanding. *Frontiers in Psychology*, *8*(FEB), 1–11. https://doi.org/10.3389/fpsyg.2017.00199

Marino, B.F.M., Gough, P. M., Gallese, V., Riggio, L., & Buccino, G. (2013). How the motor system handles nouns : a behavioral study. *Psychological Research*, *77*, 64–73.

https://doi.org/10.1007/s00426-011-0371-2

Marino, B. F.M., Gallese, V., Buccino, G., & Riggio, L. (2012). Language sensorimotor specificity modulates the motor system. *Cortex*, *48*(7), 849–856. https://doi.org/10.1016/j.cortex.2010.12.003

Marino, Bs F M, Sirianni, M., Volta, R. D., Magliocco, F., Silipo, F., Quattrone, A., … Joshua, P. (2014). Viewing photos and reading nouns of natural graspable objects similarly modulate motor responses. *Frontiers in Human Neuroscience*, *8*(December), 1–10. https://doi.org/10.3389/fnhum.2014.00968

Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L., & Ungerleider, L. G. (1995). Discrete cortical regions associated with knowledge of color and knowledge of action. *Science*, *270*(5233), 102–105. https://doi.org/10.1126/science.270.5233.102

Martin, A. (2016). GRAPES — Grounding representations in action , perception , and emotion systems : How object properties and categories are represented in the human brain. *Psychonomic Bulletin & Review*, 979–990. https://doi.org/10.3758/s13423-015-0842-3

Martin, A., Wiggs, C. L., Ungerleider, L. G., & Haxby, J. V. (1996). Neural correlates of category-specific knowledge. *Nature*. https://doi.org/10.1038/379649a0

Martinovic, J., Gruber, T., & Müller, M. M. (2008). Coding of visual object features and feature conjunctions in the human brain. *PLoS ONE*, *3*(11). https://doi.org/10.1371/journal.pone.0003781

Masson, M. E. J., Bub, D. N., & Breuer, A. T. (2011). Priming of Reach and Grasp Actions by Handled Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(5), 1470–1484. https://doi.org/10.1037/a0023509

McKeefry, D. J., & Zeki, S. (1997). The position and topography of the human colour centre as revealed by functional magnetic resonance imaging. *Brain*, *120*(12), 2229–2242. https://doi.org/10.1093/brain/120.12.2229

Miceli, G., Fouch, E., Capasso, R., Shelton, J. R., Tomaiuolo, F., & Caramazza, a. (2001). The dissociation of color from form and function knowledge. *Nature Neuroscience*, *4*(6), 662–667. https://doi.org/10.1038/88497

Miller, E. K., & Cohen, J. D. (2001). An integrate theory of PFC function. *Annual Review of*

Neuroscience, *24*, 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Milner, A. D., & Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia*, *46*(3), 774–785. https://doi.org/10.1016/j.neuropsychologia.2007.10.005

Mishkin, M., & Ungerleider, L. G. (1982). Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. *Behavioural Brain Research*, *6*(1), 57–77. https://doi.org/10.1016/0166-4328(82)90081-X

Morey, R. D. (2008). Confidence Intervals from Normalized Data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, *4*(2), 61–64. https://doi.org/10.20982/tqmp.04.2.p061

Murata, A., Gallese, V., Luppino, G., Kaseda, M., & Sakata, H. (2000). Selectivity for the Shape, Size, and Orientation of Objects for Grasping in Neurons of Monkey Parietal Area AIP. *J Neurophysiol*, *83*, 2580–2601.

Naor-Raz, G., Tarr, M. J., & Kersten, D. (2003). Is color an intrinsic property of object representation? *Perception*, *32*(6), 667–680. https://doi.org/10.1068/p5050

Nelissen, K., & Vanduffel, W. (2011). Grasping-related functional MRI brain responses in the macaque monkey. *Journal of Neuroscience*, *31*(22), 8220–8229. https://doi.org/10.1523/JNEUROSCI.0623-11.2011.Grasping-related

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Osborne, J. W., & Carolina, N. (2010). Improving your data transformations : Applying the Box-Cox transformation, *15*(12).

Pappas, Z. (2014). Dissociating Simon and affordance compatibility effects: Silhouettes and photographs. *Cognition*, *133*(3), 716–728. https://doi.org/10.1016/j.cognition.2014.08.018

Paulesu, E., Harrison, J., Baron-cohen, S., Watson, J. D. G., Goldstein, L., Heather, J., … Frith, C. D. (1995). The physiology of coloured hearing. A PET activation study of colour-word synaesthesia. *Brain*, *118*(4), 1073. https://doi.org/10.1093/brain/118.4.1073

Pavese, A., & Buxbaum, L. J. (2002). Action matters : The role of action plans and object affordances in selection for action. *Visual Cognition*, *9*, 559–590. https://doi.org/10.1080/13506280143000584

Pellicano, A., Iani, C., Borghi, A. M., Rubichi, S., & Nicoletti, R. (2010). Simon-like and functional affordance effects with tools: The effects of object perceptual discrimination and object action state. *The Quarterly Journal of Experimental Psychology*, *63*(11), 2190–2201. https://doi.org/10.1080/17470218.2010.486903

Phillips, J. C., & Ward, R. (2002). S-R correspondence effects of irrelevant visual affordance: Time course and specificity of response activation. *Visual Cognition*, *9*(4–5), 540–558. https://doi.org/10.1080/13506280143000575

Pisella, L., Binkofski, F., Lasek, K., & Rossetti, Y. (2006). No double-dissociation between optic ataxia and visual agnosia: Multiple sub-streams for multiple visuo-manual integrations. *Neuropsychologia*, *44*(May 2017), 2734–2748. https://doi.org/10.1016/j.neuropsychologia.2006.03.027

Price, C. J., & Humphreys, G. W. (1989). The effects of surface detail on object categorization and naming. *The Quarterly Journal of Experimental Psychology Section A*, *41*(4), 797–828. https://doi.org/10.1080/14640748908402394

Proctor, R. W., Lien, M. C., & Thompson, L. (2017). Do silhouettes and photographs produce fundamentally different object-based correspondence effects? *Cognition*, *169*(August), 91–101. https://doi.org/10.1016/j.cognition.2017.08.009

Proctor, R. W., & Reeve, T. G. (1990). Research on Stimulus-Response Compatibility: Toward a Comprehensive Account. *Advances in Psychology*, *65*(C), 483–494. https://doi.org/10.1016/S0166-4115(08)61234-0

Pulvermüller, F. (2002). A brain perspective on language mechanisms: from discrete neuronal ensembles to serial order. *Progress in Neurobiology*, *67*(2), 85–111. https://doi.org/https://doi.org/10.1016/S0301-0082(02)00014-X

Pulvermüller, F., & Fadiga, L. (2010). Active perception: Sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience*, *11*(5), 351–360. https://doi.org/10.1038/nrn2811

Pulvermüller, F., Härle, M., & Hummel, F. (2001). Walking or talking?: Behavioral and neurophysiological correlates of action verb processing. *Brain and Language*, *78*(2), 143–168.

Pulvermüller, F., Shtyrov, Y., & Ilmoniemi, R. (2005). Brain signatures of meaning access in action word recognition. *Journal of Cognitive Neuroscience*, *17*(6), 884–892. https://doi.org/10.1162/0898929054021111

Pylyshyn, Z. W. (1984). *Computation and cognition*. MIT press Cambridge, MA.

Raos, V., Umiltá, M.-A., Gallese, V., & Fogassi, L. (2006). Functional Properties of Grasping-Related Neurons in the Ventral Premotor Area F5 of the Macaque Monkey. *Journal of Neurophysiology*, *95*(2), 709–729. https://doi.org/10.1152/jn.00463.2005

Rice, N. J., Valyear, K. F., Goodale, M. A., Milner, A. D., & Culham, J. C. (2007). Orientation sensitivity to graspable objects: An fMRI adaptation study. *NeuroImage*, *36*(SUPPL. 2). https://doi.org/10.1016/j.neuroimage.2007.03.032

Richter, T., Zwaan, R. A., & Hoever, I. (2009). Acquiring experiential traces in word – referent learning. *Memory & Cognition*, *37*(8), 1187–1196. https://doi.org/10.3758/MC.37.8.1187

Riggio, L., Iani, C., Gherri, E., Benatti, F., Rubichi, S., & Nicoletti, R. (2008). The role of attention in the occurrence of the affordance effect. *Acta Psychologica*, *127*(2), 449–458. https://doi.org/10.1016/j.actpsy.2007.08.008

Rizzolatti, G., Camarda, R., Fogassi, L., Gentilucci, M., Luppino, G., & Matelli, M. (1988). Functional organization of inferior area 6 in the macaque monkey - II. Area F5 and the control of distal movements. *Experimental Brain Research*. https://doi.org/10.1007/BF00248742

Rizzolatti, G., Luppino, G., & Matelli, M. (1998). The organization of the cortical motor system: New concepts. *Electroencephalography and Clinical Neurophysiology*, *106*(4), 283–296. https://doi.org/10.1016/S0013-4694(98)00022-4

Rizzolatti, G., & Matelli, M. (2003). Two different streams form the dorsal visual system: Anatomy and functions. *Experimental Brain Research*, *153*(2), 146–157. https://doi.org/10.1007/s00221-003-1588-0

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, *3*(2), 131–141.

Rizzolatti, G., & Luppino, G. (2001). The cortical motor system. *Neuron*, *31*(6), 889–901. https://doi.org/10.1016/S0896-6273(01)00423-8

Rossetti, Y., Revol, P., McIntosh, R., Pisella, L., Rode, G., Danckert, J., … Milner, A. D. (2005). Visually guided reaching: Bilateral posterior parietal lesions cause a switch from fast visuomotor to slow cognitive control. *Neuropsychologia*, *43*(2 SPEC. ISS.), 162–177. https://doi.org/10.1016/j.neuropsychologia.2004.11.004

Rounis, E., Van Polanen, V., & Davare, M. (2018). A direct effect of perception on action when grasping a cup. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-017-18591-5

Rueschemeyer, S.-A., van Rooij, D., Lindemann, O., Willems, R. M., & Bekkering, H. (2010). The function of words: distinct neural correlates for words denoting differently manipulable objects. *Journal of Cognitive Neuroscience*, *22*(8), 1844–1851. https://doi.org/10.1162/jocn.2009.21310

Rüttiger, L., Braun, D. I., Gegenfurtner, K. R., Petersen, D., Schönle, P., & Sharpe, L. T. (1999). Selective color constancy deficits after circumscribed unilateral brain lesions. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *19*(8), 3094–3106.

Sacks, O. (1995). *An Anthropologist on Mars : Seven Paradoxical Tales*. New York City, New York: Alfred A. Knopf.

Sakata, H., Taira, M., Murata, A., & Mine, S. (1995). Neural mechanisms of visual guidance of hand action in the parietal cortex of the monkey. *Cerebral Cortex*, *5*(5), 429–438. https://doi.org/10.1093/cercor/5.5.429

Sakreida, K., Effnert, I., Thill, S., Menz, M. M., Jirak, D., Eickhoff, C. R., … Binkofski, F. (2016). Affordance processing in segregated parieto-frontal dorsal stream sub-pathways. *Neuroscience and Biobehavioral Reviews*, *69*, 89–112. https://doi.org/10.1016/j.neubiorev.2016.07.032

Santana, E. J., & De Vega, M. (2013). An ERP study of motor compatibility effects in action language. *Brain Research*, *1526*, 71–83. https://doi.org/10.1016/j.brainres.2013.06.020

Sarlegna, F. R., & Mutha, P. K. (2015). The influence of visual target information on the online control of movements. *Vision Research*, *110*(PB), 144–154. https://doi.org/10.1016/j.visres.2014.07.001

Sato, M., Mengarelli, M., Riggio, L., Gallese, V., & Buccino, G. (2008). Task related modulation of the motor system during language processing. *Brain and Language*, *105*(2), 83–90. https://doi.org/10.1016/j.bandl.2007.10.001

Schein, S. J., & Desimone, R. (1990). Spectral properties of V4 neurons in the macaque. *The Journal of Neuroscience*, *10*(10), 3369–3389.

Schoppig, A., Clarke, S., Walsh, V., Assal, G., Meuli, R., & Cowey, A. (1999). Short-term memory for colour following posterior hemispheric lesions in man. *Neuroreport*, *10*(6), 1379–1384.

Schulz, M. F., & Sanocki, T. (2003). Time Course of Perceptual Grouping by Color. *Psychological SciencesResearch*, *14*(1), 26–30. https://doi.org/doi:10.1515/LANGCOG.2010.004

Scorolli, C., & Borghi, A. M. (2007). Sentence comprehension and action: Effector specific modulation of the motor system. *Brain research*, *1130*, 119-124.

Scorolli, C., & Borghi, A. M. (2015). Square bananas, blue horses: The relative weight of shape and color in concept recognition and representation. *Frontiers in Psychology*, *6*(OCT), 1–13. https://doi.org/10.3389/fpsyg.2015.01542

Scorolli, C., Borghi, A. M., & Glenberg, A. (2009). Language-induced motor activity in bi-manual object lifting. Experimental Brain Research, 193(1), 43-53.

Scott, S. H., Cluff, T., Lowrey, C. R., & Takei, T. (2015). Feedback control during voluntary motor actions. *Current Opinion in Neurobiology*. Elsevier Ltd. https://doi.org/10.1016/j.conb.2015.03.006

Shuren, J. E., Brott, T. G., Schefft, B. K., & Houston, W. (1996). Preserved color imagery in an achromatopsic. *Neuropsychologia*, *34*(6), 485–489. https://doi.org/10.1016/0028-3932(95)00153-0

Simmons, W. K., Ramjee, V., Beauchamo, S. M., McRae, K., Martin, A., & Barsalou, L. W. (2007). A common neural substrate for perceiving and knowing about colo. *Neuropsychologia*, *45*(12), 2802–2810. https://doi.org/10.1016/j.neuropsychologia.2007.05.002.A

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, *81*(1), 174–176. https://doi.org/10.1037/h0027448

Singmann, H., Bolker, B., Westfall, J., & Frederik, A. (2016). afex: Analysis of Factorial Experiments. R package version 0.16-1. Retrieved from https://cran.r-project.org/package=afex

Song, X., Chen, J., & Proctor, R. W. (2014). Correspondence effects with torches: Grasping affordance or visual feature asymmetry? *The Quarterly Journal of Experimental Psychology*, *67*(4), 665–675. https://doi.org/10.1080/17470218.2013.824996

Stasenko, A., Garcea, F. E., Dombovy, M., & Mahon, B. Z. (2014). When concepts lose their color: A case of object color knowledge impairment. *Cortex.*, *58*, 217–238. https://doi.org/10.1038/jid.2014.371

Symes, E., Ellis, R., & Tucker, M. (2005). Dissociating object-based and space-based affordances. *Visual Cognition*, *12*(7), 1337–1361. https://doi.org/10.1080/13506280444000445

Tanaka, J. W., & Presnell, L. M. (1999). Color diagnosticity in object recognition. *Perception & Psychophysics*, *61*(6), 1140–1153. https://doi.org/10.3758/BF03207619

Tanaka, J., Weiskopf, D., & Williams, P. (2001). The role of color in high-level vision. *Trends in Cognitive Sciences*, *5*(5), 211–215.

Taylor, L. J., Lev-Ari, S., & Zwaan, R. A. (2008). Inferences about action engage action systems. *Brain and Language*, *107*(1), 62–67. https://doi.org/10.1016/j.bandl.2007.08.004

Taylor, L. J., & Zwaan, R. A. (2008). Motor resonance and linguistic focus, *61*(6), 896–904. https://doi.org/10.1080/17470210701625519

Taylor, L. J., & Zwaan, R. A. (2009). Action in cognition : The case of language. *Language and Cognition*, *1*(1), 45–58.

Taylor, L. J., & Zwaan, R. A. (2010). Grasping spheres, not planets. *Cognition*, *115*(1), 39–45. https://doi.org/10.1016/j.cognition.2009.11.006

R Core Team (2018). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., … Perani, D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of Cognitive Neuroscience*, *17*(2), 273–281. https://doi.org/10.1162/0898929053124965

Therriault, D. J., Yaxley, R. H., & Zwaan, R. A. (2009). The role of color diagnosticity in object recognition and representation. *Cognitive Processing*, *10*(4), 335–342. https://doi.org/10.1007/s10339-009-0260-4

Thompson-Schill, S. L. (2003). Neuroimaging studies of semantic memory inferring "how" from "where", *41*, 280–292.

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 830–846. https://doi.org/10.1037/0096-1523.24.3.830

Tucker, M., & Ellis, R. (2001). Grasp potentiation by visual objects The potentiation of grasp types during visual object categorization, *8*(6), 769–800. https://doi.org/10.1080/13506280042000144

Tucker, M., & Ellis, R. (2004). Action priming by briefly presented objects. *Acta Psychologica*, *116*(2), 185–203. https://doi.org/10.1016/j.actpsy.2004.01.004

Vainio, L., Ellis, R., & Tucker, M. (2007). The role of visual attention in action priming. *Quarterly Journal of Experimental Psychology*, *60*(2), 241–261. https://doi.org/10.1080/17470210600625149

Vainio, L., Symes, E., Ellis, R., Tucker, M., & Ottoboni, G. (2008). On the relations between action planning, object identification, and motor representations of observed actions and objects. *Cognition*, *108*(2), 444–465. https://doi.org/10.1016/j.cognition.2008.03.007

Van Essen, D. C., & Zeki, S. M. (1978). The topographic organization of rhesus monkey prestriate cortex. *The Journal of Physiology*, *277*, 193–226. https://doi.org/10.1113/jphysiol.1978.sp012269

Weiner, K. S., & Grill-Spector, K. (2012). The improbable simplicity of the fusiform face area. *Trends in Cognitive Sciences*, *16*(5), 251–254. https://doi.org/10.1016/j.tics.2012.03.003

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record*, *58*(3), 475-482.

Wiggs, C. L., Weisberg, J., & Martin, A. (1998). Neural correlates of semantic and episodic memory retrieval. *Neuropsychologia*, *37*(1), 103–118. https://doi.org/10.1016/S0028-3932(98)00044-X

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636. https://doi.org/10.3758/BF03196322

Witzel, C., Valkova, H., & Hansen, T. (2011). Object knowledge modulates colour appearance, *2*, 13–49.

Woodworth, R. S. (1899). Accuracy of voluntary movement. The Psychological Review: Monograph Supplements, 3(3), i.

Wurm, L. H., Legge, G. E., Isenberg, L. M., & Luebker, A. (1993). Color improves object recognition in normal and low vision. *Journal of Experimental Psychology. Human Perception and Performance*, *19*(4), 899–911. https://doi.org/10.1037/0096-1523.19.4.899

Young, G. (2006). Are different affordances subserved by different neural pathways? *Brain and Cognition*, *62*, 134–142. https://doi.org/10.1016/j.bandc.2006.04.002

Zeki, S. (1983a). Colour coding in the cerebral cortex: The reaction of cells in monkey visual cortex to wavelengths and colours. *Neuroscience*, *9*(4), 741–765. https://doi.org/10.1016/0306-4522(83)90265-8

Zeki, S. (1983b). Colour coding in the cerebral cortex: The responses of wavelength-selective and colour-coded cells in monkey visual cortex to changes in wavelength composition. *Neuroscience*, *9*(4). https://doi.org/10.1016/0306-4522(83)90266-X

Zeki, S. (1983c). The distribution of wavelength and orientation selective cells in different areas of monkey visual cortex. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, *217*(1209), 449–470. https://doi.org/10.1098/rspb.1983.0020

Zeki, S., & Marini, L. (1998). Three cortical stages of colour processing in the human brain. *Brain*, *121*(9), 1669–1685. https://doi.org/10.1093/brain/121.9.1669

Zeki, S., Watson, J. D. G., Lueck, C. J., Friston, K. J., Kennard, C., & Frackowiak, R. S. J.

(1991). A direct demonstration of functional specialization in human visual cortex. *Journal of Neuroscience*, *11*(3), 641–649. https://doi.org/10.1523/jneurosci.11-03-00641.1991

Zhong, Y., & Rockland, K. S. (2003). Inferior Parietal Lobule Projections to Anterior Inferotemporal Cortex (AreaTE) in Macaque Monkey. *Cerebral Cortex*, *13*(May), 527–540. https://doi.org/10.1093/cercor/13.5.527

Zwaan, R. A., & Pecher, D. (2012). Revisiting Mental Simulation in Language Comprehension : Six Replication Attempts. *Plose One*, *7*(12). https://doi.org/10.1371/journal.pone.0051382

Zwaan, R. A., & Taylor, L. J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology: General*, *135*(1), 1–11. https://doi.org/10.1037/0096-3445.135.1.1

Appendix

A) Stimuli selection and validation for the Experiment 1 and 2

Thirty-two pictures of everyday objects were selected from Google image research and submitted to a chromaticity manipulation. Sixteen pictures refer to artefacts and sixteen to natural objects. Half of each category are usually grasped with precision (thumb-index) grip and eight with power (whole) hand grip. The chromaticity of each picture was inverted using MATLAB R2017b, in two steps. First, we converted the pictures in L*a*b colour space, and subsequently, we changed the a or b values to their opposites (total pictures = 64). In this way, the physical luminance was taken constant between each pairs picture (see Figure 17) and measured through an external luminance meter (Minolta luminance meter LS-100)

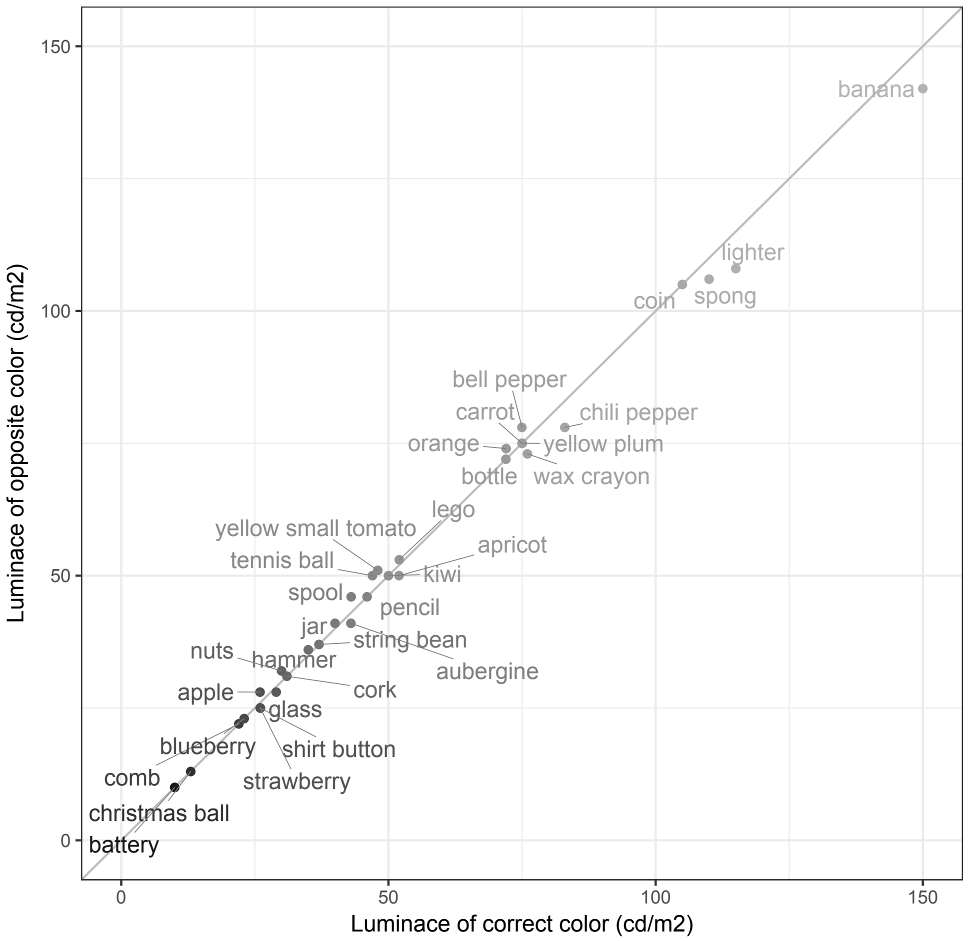


Figure 17 Luminance values for each object are plotted, in the x-axis, as a function of correct colour luminance, and in y-axis as a function of luminance with inverted colour. As the graph shows, for each object the two luminance values are paired. Black to grey gradient indicates the increment of luminance across stimuli.

Sixteen independent participants (11 Females; Mean age = 26, SD = 3.2), without any colour vision deficit, evaluated the pictures by means of visual analogue scale (VAS) administered by computer task. Participants had to respond to three questions for each picture. The first question aimed to assess how usually the object depicted is grasped. The second question aimed to assess how much familiar the object is. Finally, the third question is a direct question on the prototypicality of the object colour. Visual inspection showed that, independently of the category (Figure 18 - panel A), participants correctly classified the object grasp. Moreover, all objects were considered familiar if shown with the correct colour and slightly less familiar with the incorrect one (Figure 18 - panel B). Finally, the colour question highlighted colour as more prototypical for natural object in comparison to artefacts (Figure 18 - panel C).

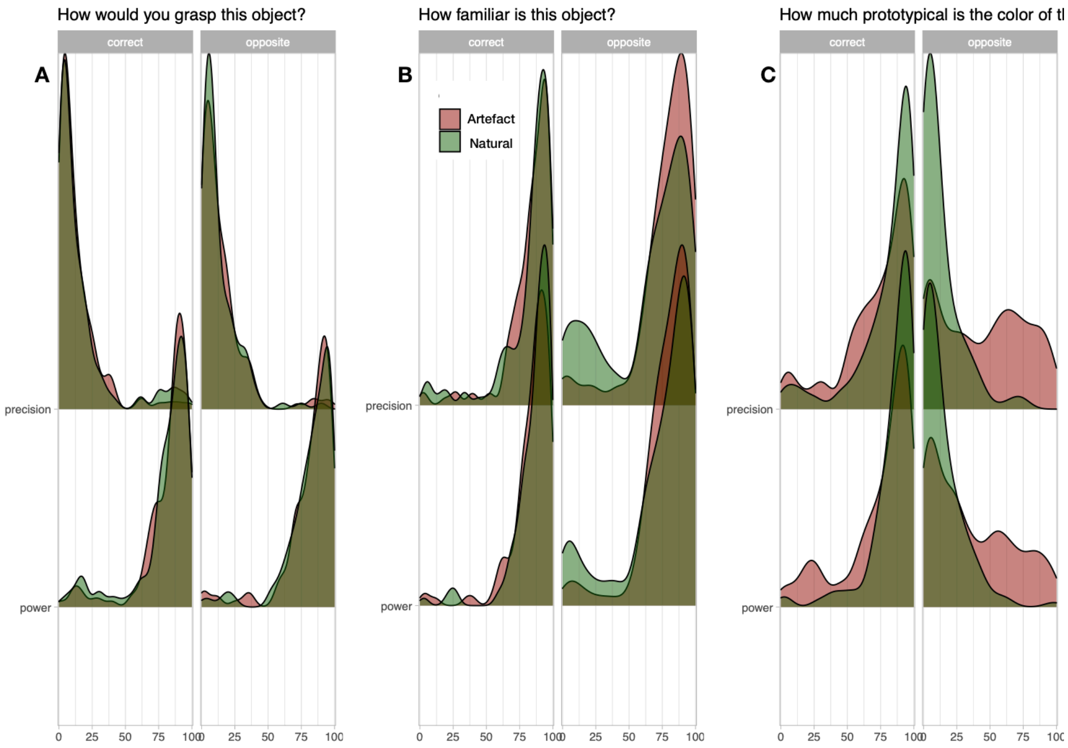


Figure 18. Plots of the distributions for the three questions used in the validation phase. Each panel refers to a single question

VAS results were submitted to three linear mixed models, one for each question, with Category, Grasp and Colour as fixed effects and both the stimuli and subjects as random factors. For each model, t > |2| is considered a reliable value. Results are reported in Table 1.

The first model showed only the effect of grasp. As previously presented, participants correctly classified the objects as power or precision objects.

The second model showed that the judgment about the familiarity of the objects was affected by the interaction between Colour and Category (Table 14). Post-hoc analysis, with Tukey HSD correction, highlights that natural objects with opposite colour are considered statistically less familiar (all comparisons with natural-opposite showed p < 0.0015) as compared to all the other conditions.

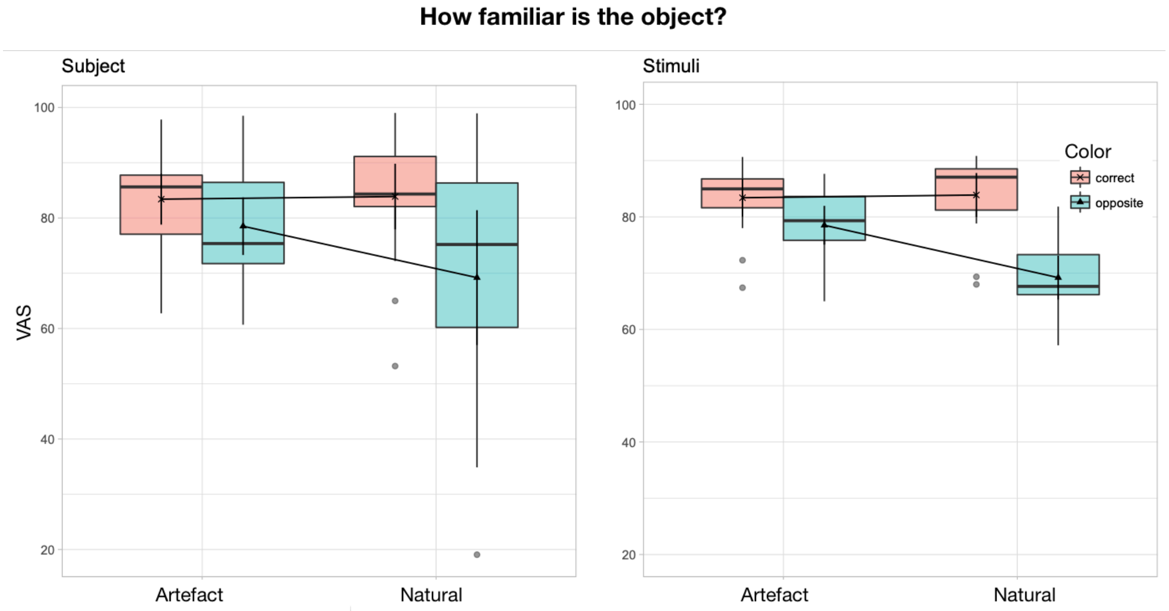


Figure 19. The figure shows the interaction between OC and Colour factors for Question 2. In the left panel, the results with Subjects as random intercept are reported; instead in the right panel, the results are plotted with Stimuli as random intercept. For both graphs, values for correct colour are shown in pink, and values for opposite colour object in light blue. The points inside the boxplot refer to means with associated standard errors.

Finally, the analysis of Question 3 showed that also here the interaction between Colour and Category is significant (Table 14). As shown in Figure 4, opposite colour is less prototypical both for artefacts and natural objects. Post-hoc comparisons showed that this difference is significant for both categories (ps < 0.001). Instead, no difference was found between categories and objects displayed with correct colour (p = 0.21).

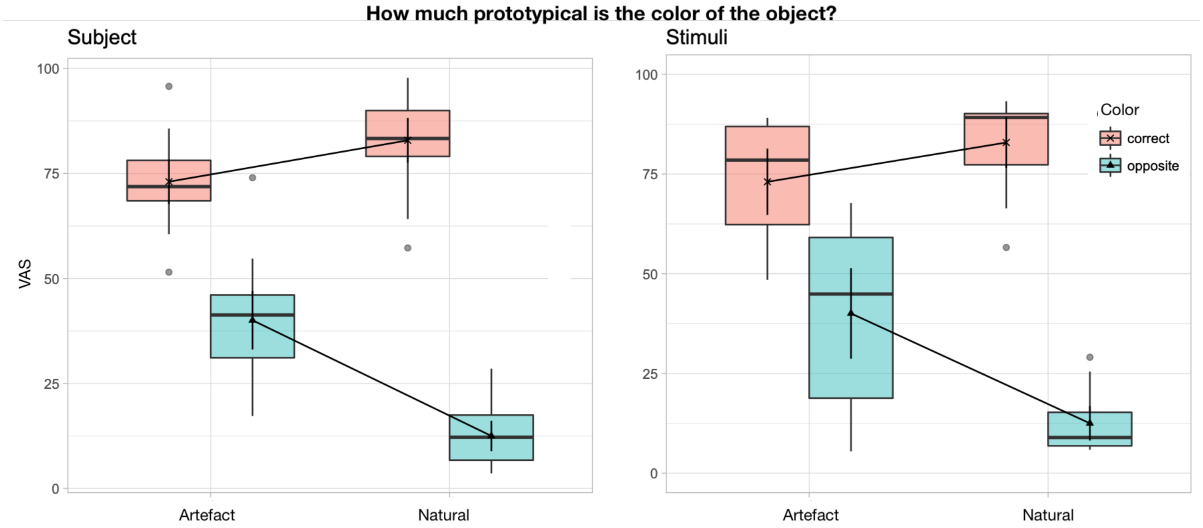


Figure 20. The figure shows the interaction between OC and Colour factors for the Question 3 (see Figure 3 for the difference between the two graphs and colour coding).

To sum up, participants correctly classified the objects based on their usually grasp. Moreover, the colour of the object affects both the familiarity judgment (Question 2) and, as expected, the direct judgment on prototypicality of colour (Question 3). Unexpected, it seems that also the artefacts selected have a prototypical colour as the natural ones, even if the difference is less marked as compared with natural objects. No one object deviated considerably from the results of the models (as showed by the stimuli panels of the Figures 18 and 21) and consequently, all of them were used in Experiments 1 and 2, and partially Experiment 3. Finally, results for all stimuli in function of the three questions are shown in the graph below (Figure 21).

	VAS – Question 1				VAS – Question 2				VAS – Question 3				
Predictors	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*	*CI*	*t*	*p*	*Estimates*
Category	47.67	45.16 – 50.18	0.03	0.980	80.96	79.32 – 82.59	2.64	**0.011**	83.18	79.35 – 87.00	2.27	0.027	83.18
Grasp	81.04	78.53 – 83.55	26.08	**<0.001**	80.50	78.87 – 82.14	1.96	0.07	78.55	74.72 – 82.37	-0.10	0.917	78.55
Colour	47.66	46.56 – 48.75	0.03	0.974	83.64	82.01 – 85.28	5.86	**<0.001**	104.60	100.78 – 108.43	13.25	<0.001	104.60
Category:Grasp	47.97	45.46 – 50.48	0.26	0.798	77.60	75.97 – 79.24	-1.38	0.174	77.05	73.22 – 80.87	-0.87	0.386	77.05
Category:Colour	47.51	46.41 – 48.60	-0.24	0.813	76.30	74.67 – 77.94	-2.93	**0.005**	69.40	65.57 – 73.22	-4.79	<0.001	69.40
Grasp:Colour	47.02	45.92 – 48.11	-1.11	0.267	78.22	76.58 – 79.85	-0.64	0.524	80.53	76.71 – 84.36	0.91	0.365	80.53
Category:Grasp:Colour	48.50	47.41 – 49.60	1.55	0.123	79.09	77.46 – 80.73	0.41	0.683	79.57	75.74 – 83.39	0.42	0.678	79.57
Random Effects													
σ^2	328.10				359.44				364.64				
$\tau_{00\ stimuli}$	41.00				21.90				213.89				
$\tau_{00\ ss}$	8.20				114.34				38.57				
Observations	1054				1054				1054				
Marginal R^2 / Conditional R^2	0.748 / 0.780				0.074 / 0.328				0.554 / 0.736				

Table 14: Results of the three linear mixed models. Reliable values are reported in bold

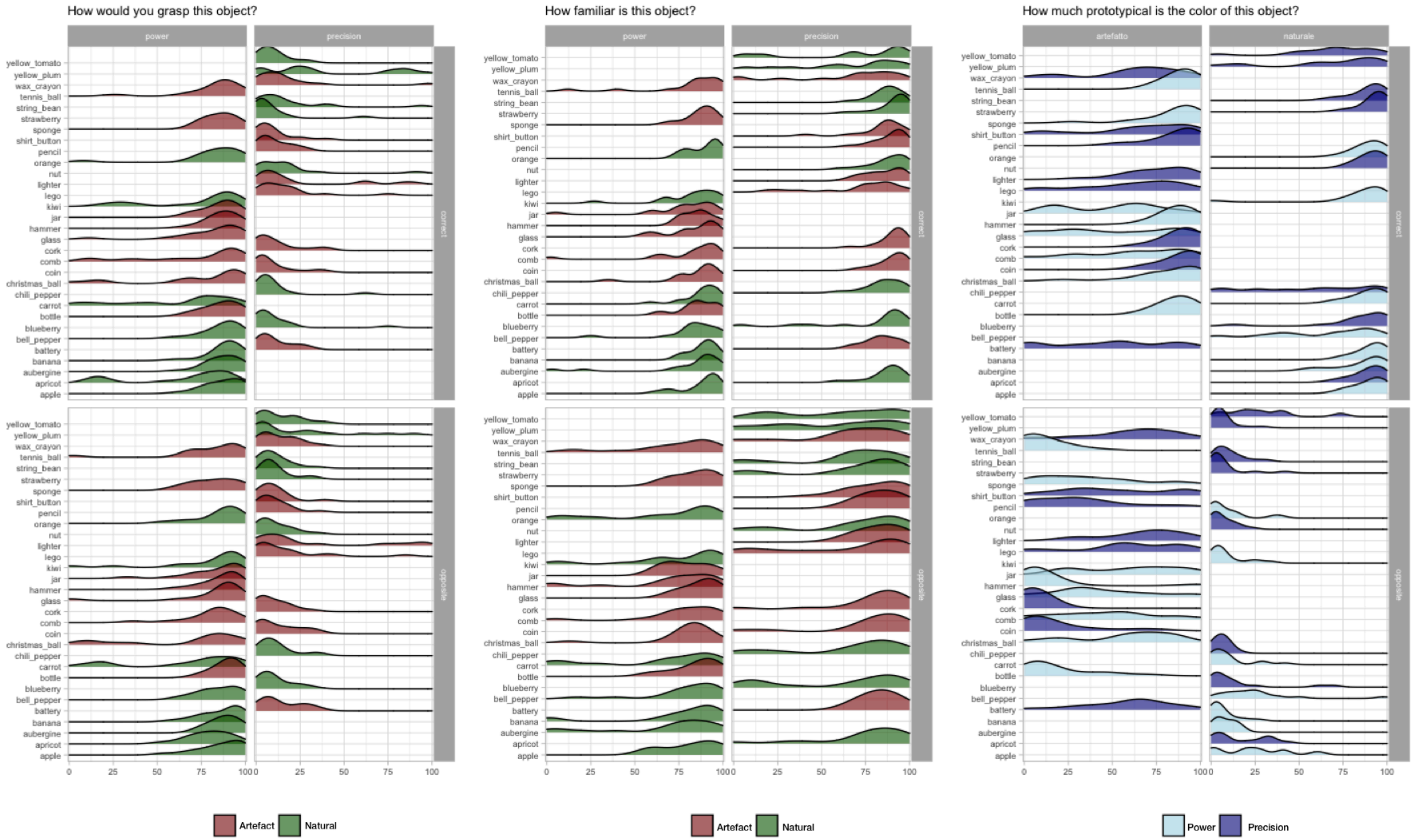


Figure 21. The joy plots show distribution of VAS values for each object picture. Each panel refers to one question.

B) Experiment 3 - List of stimuli

Object	**Dangerousness**
orange	Not dangerous
carrot	Not dangerous
kiwi	Not dangerous
apple	Not dangerous
potato	Not dangerous
pear	Not dangerous
aubergine	Not dangerous
bell pepper	Not dangerous
spiky zucchini	Dangerous
cactus	Dangerous
artichoke	Dangerous
chestnut shell	Dangerous
spiky seashell 1	Dangerous
spiky seashell 2	Dangerous
sea urchin	Dangerous
prickly pear	Dangerous

Table 15. List of stimuli used in Experiment 3

C) Experiment 4 – Nouns validation

We administered to 16 independent participants a questionnaire aimed to assess whether: 1) the object denoted by the noun is preferably taken with one or two hands, and 2) if the object is grasped with two fingers (precision grip) or with the whole hand (power grip). The questionnaire, administered paper and pen, was structured with a 7-point Likert scale. For the first question, score 1 indicated that the noun referred to one-handed object and 7 to two-handed object; for the second question, score 1 indicated that the noun referred to an object preferentially grasped with the whole hand and score 7 preferentially grasped with thumb and index fingers. The data of the first question showed that participants indicated that all stimuli could be grasped with one hand (M = 1.34, SE = 0.9, SE = 0.07). None of the stimuli showed an average score higher than 3.5 of the Likert scale (min = 1, max = 2.5). In addition, we performed a repeated measured ANOVA, with Object Category (OC, 2 levels: natural vs man-made) and Object Grasp (OG, 2 levels: precision vs power) as within-participants factors. Results showed that only the main effect of the OG, F(1,15) = 36.67, $p < 0.0001$, was significant. These results indicate that participants assigned higher scores to power object nouns (M = 1.5, SD= 1, SE = 0.06) in comparison to precision object nouns (M = 1.1, SD = 0.4, SE = 0.027).

Concerning the second question, participants correctly classified the objects. Precision object nouns showed an average score of 6.4 (SD= 0.88, SE = 0.054); instead power object nouns presented an average score of 1.6 (SD = 0.93, SE = 0.058). No noun in each category presented mean scores above or below 3.5 (precision objects: min = 5.56, max = 6.94; power objects: min = 1.06, max = 2.19). Repeated measures ANOVA with OC and OG as within-participants factors showed that the main effects of the OG [F(1,15) = 1886.7, $p < 0.001$] and OC [F(1,15) = 6.8, $p = 0.02$] were significant. Also the interaction [F(1,15) = 6.35, $p = 0.023$] reached significance. Pairwise post-hoc comparisons with Bonferroni's correction showed that, for both categories, the difference between precision and power objects was significant (natural: $p < 0.0001$; man-made: $p< 0.0001$). Moreover, the scores of power objects differed between natural and man-made nouns (natural = 1.35, man-made = 1.78; $p = 0.01$).

Two separates one-way ANOVAs on Number of syllables and Word Frequency, with Category as between-subject factor, do not reveal any significance difference between man-made and natural object nouns (N. of syllables: F < 1, p > 0.7; Frequency: F < 1, p > 0.3)

Nouns		Grasp	Category	Frequency	N. of syllables	Mean rating Q1	Mean rating Q2
foglia	leaf	precision	natural	28800000	2	1.6	6.4
noce	nut	precision	natural	4010000	2	1	6.0
conchiglia	seashell	precision	natural	5380000	3	1	6.2
mandorla	almond	precision	natural	7890000	3	1	6.7
castagna	chestnut	precision	natural	13800000	3	1.1	6.4
guscio	husk	precision	natural	10400000	2	1.2	6.2
fagiolo	bean	precision	natural	2700000	3	1	6.6
oliva	olive	precision	natural	17100000	2	1	6.8
pigna	pinecone	power	natural	2700000	2	1	1.7
carota	carrot	power	natural	12000000	3	1.1	3.3
ramo	tree branch	power	natural	120000000	2	2.5	1.7
cocco	coconut	power	natural	32300000	2	3.4	1.1
carbone	coal	power	natural	91700000	3	1.6	2.2
sasso	stone	power	natural	50900000	2	1.6	2.1
peperone	bell pepper	power	natural	2520000	4	1.1	1.6
patata	potato	power	natural	34000000	2	1	1.6
fiammifero	matchstick	precision	man-made	1014000	4	1	6.9
foglio	sheet	precision	man-made	38000000	2	1.6	5.7
vetrino	slide (petri dish)	precision	man-made	7110000	3	1.1	6.7
biglia	marble	precision	man-made	5100000	2	1.1	6.4
chiodo	nail	precision	man-made	14300000	2	1	6.8
tappo	stopper	precision	man-made	22300000	2	1.3	6.6
provetta	test tube	precision	man-made	1120000	3	1	6
tazzina	coffee cup	precision	man-made	1970000	3	1.1	5.7
cellulare	cellphone	power	man-made	80500000	4	1.2	1.4
pagnotta	bun	power	man-made	2320000	3	1.4	1.1
bicchiere	glass	power	man-made	2520000	3	1	1.1
bottiglia	bottle	power	man-made	35200000	3	1.8	1.1
pinza	pliers	power	man-made	50600000	2	1.1	1.8
piatto	plate	power	man-made	92600000	2	2.4	1.7
teiera	teapot	power	man-made	1980000	2	1.9	1.4
barattolo	jar	power	man-made	9240000	4	1.3	1.2

Table 16. Table of words used in Experiment 4

D) Experiment 5 – Validation of noun and disadvantageous adjective combinations

In Experiment 5 combinations of nouns and adjectives were used. The noun and disadvantageous adjective combinations were subjected to a further validation. Twenty independent participants were asked to evaluate each combination through four questions. The first question concerned how easy/difficult is to grasp the object indicated in the linguistic combination, taking into account the quality expressed by the adjective. The second question concerned the familiarity of the combination. The third question required to judge the chance of using that noun-adjective combination. Finally, the fourth question concerned the easiness of imagining the object indicated by the noun in relation to the quality expressed by the adjective. The questionnaire, administered paper and pen, was structured with a 7-point Likert scale.

For the first question, the score equal to 1 indicated that it was extremely easy to grasp the object, conversely, the score 7 indicated an extremely difficult grasp of the object. The data showed that participants found quite difficult to grasp the object described in the combination (M = 5, SD = 2, SE = 0.075). We performed a repeated measures ANOVA with Object Category (OC, 2 levels: natural vs man-made) and Object Grasp (OG, 2 levels: precision vs power) as within-participants factors (the same ANOVA model has been performed for all the questions). Results showed only the main effect of the OC [F(1,21) = 20.6, $p < 0.001$]. Disadvantageous adjectives combined with man-made nouns were evaluated slightly more difficult to grasp (M = 5.3, SD = 1.8, SE= 0.09) in comparison to the combination with natural nouns (M = 4.7, SD = 1.9, SE = 0.1). As to the second question, score equal to 7 indicated that the combinations were completely familiar, and the score 1 completely unfamiliar; the data showed that participants considered all the combinations quite familiar (M = 4.9, SD = 1.8, SE= 0.07). The ANOVA revealed the main effect of OC [F(1,21) = 19.5, $p < 0.001$], indicating that natural nouns combinations were more familiar (M = 5.1, SD = 1.7, SE = 0.09) then the man-made ones (M = 4.6, SD = 1.8, SE = 0.1). Also, the interaction between the two factors reached statistical significance [F(1,21) = 16.6, $p < 0.001$]. Post-hoc comparison with Bonferroni's correction showed that for natural nouns combination, the difference between the two types of grasp was significant ($p < 0.001$), indicating as more familiar the natural precision combinations (M =

5.3, SD = 1.8, SE = 0.12) than the power ones (M = 4.8, SD = 1.5, SE = 0.14). For the third question, participants evaluated the chance of using the combination as quite probable (scores equal to 7 indicate high probability; M = 4.5, SD = 1.9, SE = 0.073). The ANOVA did not show any significant difference (all $ps < 0.05$). Finally, as the fourth question the participants' scores highlighted that the combinations were easy to imagine (1 indicates extremely easy to imagine; M = 2.3, SD = 1.5, SE. = 0.05). The ANOVA showed the main effect of OC, $F(1,21) = 9.6$, $p < 0.01$, since the combinations with the nouns of denoting natural objects obtained lower scores (M = 2.1, SD = 1.4, SE = 0.07) in comparison to the man-made combinations (M = 2.4, SD = 1.6, SE = 0.08).

Nouns		**Disadvantageous Adj.**		**Colour Adjectives**		**Grasp**	**Category**
foglia	leaf	bruciata	burned	verdastra	greenish	precision	natural
noce	nut	tritata	chopped	giallastra	yellowish	precision	natural
conchiglia	sea shell	scheggiato	chipped	biancastra	whiteish	precision	natural
mandorla	almond	frantumata	crushed	marrone	brown	precision	natural
castagna	chestnut	rovente	hot	grigiastra	greyish	precision	natural
guscio	husk	tagliente	sharp	bluastro	blueish	precision	natural
fagiolo	bean	bollente	hot (boiling)	rossastro	reddish	precision	natural
oliva	olive	unta	greasy	nerastra	blackish	precision	natural
pigna	pine cone	bruciata	burned	nerastra	blackish	power	natural
carota	carrot	tritata	chopped	giallastra	yellowish	power	natural
ramo	tree branch	scheggiato	chipped	biancastro	whiteish	power	natural
cocco	coconut	frantumata	crushed	marrone	brown	power	natural
carbone	coal	rovente	hot	grigiastro	greyish	power	natural
sasso	stone	tagliente	sharp	bluastro	blueish	power	natural
peperone	bell pepper	bollente	hot (boiling)	rossastro	reddish	power	natural
patata	potato	unta	greasy	verdastra	greenish	power	natural
fiammifero	matchstick	bruciato	burned	nerastro	blackish	precision	man-made
foglio	sheet	tritato	chopped	giallastro	yellowish	precision	man-made
vetrino	slide (petri dish)	scheggiato	chipped	biancastro	whiteish	precision	man-made
biglia	marble	frantumata	crushed	marrone	brown	precision	man-made
chiodo	nail	rovente	hot	grigiastro	greyish	precision	man-made
tappo	stopper	tagliente	sharp	bluastro	blueish	precision	man-made
provetta	test tube	bollente	hot (boiling)	rossastro	reddish	precision	man-made
tazzina	coffee cup	unta	greasy	verdastra	greenish	precision	man-made

cellulare	cellphone	bruciata	burned	nerastro	blackish	power	man-made
pagnotta	bun	tritata	chopped	giallastra	yellowish	power	man-made
bicchiere	glass	scheggiato	chipped	biancastro	whiteish	power	man-made
bottiglia	bottle	frantumata	crushed	marrone	brown	power	man-made
pinza	pliers	rovente	hot	grigiastra	greyish	power	man-made
piatto	plate	tagliente	sharp	bluastro	blueish	power	man-made
teiera	teapot	bollente	hot (boiling)	rossastro	reddish	power	man-made
barattolo	jar	unta	greasy	verdastro	greenish	power	man-made

Table 17.Table of words used in Experiment 5

E) Experiment 6 – Validation of noun and shape/tactile adjective combinations

In Experiment 6 combinations of nouns and adjectives were used. We asked to eighteen independent participants to evaluate the stimuli along the same dimensions of the previous validation.

Scores of each question did not showed any significant difference between OC and Grasp. The only exception concerns the difference between the natural and artefacts in the fourth question (imagination, $F(1,17) = 6.7$, $p = 0.01$), denoting that artefact are slightly easy ($M = 5.3$, $SD = 1.48$, $SE = 0.35$) to imagine as compared to natural (4.9, $SD = 1.39$, $SE = 0.33$). Despite this difference, all the combinations are evaluated as easily to grasp ($M = 5$, $SD = 1.3$, $SE = 0.08$), quiet familiar ($M = 5.4$, $SD = 1.52$, $SE = 0.36$) and commonly used ($M = 5.6$, $SD = 1.62$, $SE = 0.38$).

Nouns		Adjectives		Grasp	Category
foglia	leaf	lunga	long	precision	natural
noce	nut	rugosa	wrinkled	precision	natural
conchiglia	sea shell	ovale	oval	precision	natural
mandorla	almond	allungata	elongated	precision	natural
castagna	chestnut	liscia	smooth	precision	natural
guscio	husk	sferico	spherical	precision	natural
fagiolo	bean	curvo	curved	precision	natural
oliva	olive	rotonda	round	precision	natural
pigna	pine cone	lunga	long	power	natural
carota	carrot	allungata	wrinkled	power	natural
ramo	tree branch	curvo	oval	power	natural
cocco	coconut	sferico	elongated	power	natural
carbone	coal	rugoso	smooth	power	natural
sasso	stone	rotondo	spherical	power	natural
peperone	bell pepper	liscio	curved	power	natural
patata	potato	ovale	round	power	natural
fiammifero	matchstick	lungo	long	precision	artefact
foglio	sheet	liscio	wrinkled	precision	artefact
vetrino	slide (petri dish)	ovale	oval	precision	artefact
biglia	marble	sferica	elongated	precision	artefact
chiodo	nail	curvo	smooth	precision	artefact
tappo	stopper	rugoso	spherical	precision	artefact
provetta	test tube	allungata	curved	precision	artefact
tazzina	coffee cup	rotonda	round	precision	artefact
cellulare	cellphone	lungo	long	power	artefact
pagnotta	bun	rugosa	wrinkled	power	artefact
bicchiere	glass	liscia	oval	power	artefact
bottiglia	bottle	allungata	elongated	power	artefact
pinza	pliers	curva	smooth	power	artefact
piatto	plate	ovale	spherical	power	artefact
teiera	teapot	rotonda	curved	power	artefact
barattolo	jar	sferico	round	power	artefact

Table 18. Table of words used in Experiment 6

F) Experiment 7 – List of words

Adjectives + noun	**Adjective category**	**Noun category**	**Grasp**
smashed apple	disadvantageous	natural	power
hot potato	antiaffordance	natural	power
broken coconut	antiaffordance	natural	power
warm aubergine	disadvantageous	natural	power
burnt charcoal	disadvantageous	natural	power
sharp stone	disadvantageous	natural	power
crashed egg	disadvantageous	natural	power
smashed strawberry	disadvantageous	natural	precision
hot bean	disadvantageous	natural	precision
broken leaf	disadvantageous	natural	precision
warm berry	disadvantageous	natural	precision
burnt mushroom	disadvantageous	natural	precision
sharp seashell	disadvantageous	natural	precision
crashed garlic	disadvantageous	natural	precision
smashed plate	disadvantageous	artefact	power
hot torch	disadvantageous	artefact	power
broken bottle	disadvantageous	artefact	power
warm cup	disadvantageous	artefact	power
burnt candle	disadvantageous	artefact	power
sharp knife	disadvantageous	artefact	power
crashed jar	disadvantageous	artefact	power
smashed teacup	disadvantageous	artefact	precision
broken pen	disadvantageous	artefact	precision
hot lighter	disadvantageous	artefact	precision
sharp screw	disadvantageous	artefact	precision
warm button	disadvantageous	artefact	precision
burnt match	disadvantageous	artefact	precision
crashed candy	disadvantageous	artefact	precision
red apple	colour	natural	power
yellow potato	colour	natural	power
brown coconut	colour	natural	power
purple aubergine	colour	natural	power
black charcoal	colour	natural	power
grey stone	colour	natural	power
white egg	colour	natural	power
red strawberry	colour	natural	precision
yellow bean	colour	natural	precision
brown leaf	colour	natural	precision
purple berry	colour	natural	precision
black mushroom	colour	natural	precision
grey seashell	colour	natural	precision
white garlic	colour	natural	precision

red plate	colour	artefact	power
yellow torch	colour	artefact	power
brown bottle	colour	artefact	power
purple cup	colour	artefact	power
black candle	colour	artefact	power
grey knife	colour	artefact	power
white jar	colour	artefact	power
red teacup	colour	artefact	precision
yellow lighter	colour	artefact	precision
brown pen	colour	artefact	precision
purple button	colour	artefact	precision
black match	colour	artefact	precision
grey screw	colour	artefact	precision
white candy	colour	artefact	precision

Table 19. List of combination used in Experiment 7

G) Edinburgh Handedness Inventory (Oldfiled, 1971)

UNIVERSITÀ DI PARMA

Dipartimento di Medicina e Chirurgia

EDINBURGH INVENTORY (OLFIELD, 1971)

Indicare la preferenza manuale nelle seguenti attività indicandola nella colonna appropriata; quando la preferenza è così forte da non poter usare l'altra mano scrivi **++.** Se non c'è preferenza scrivi **+** in entrambe le colonne

	Mano usata preferenzialmente	
Azioni	**SX**	**DX**
Scrivere		
Disegnare		
Lanciare un oggetto		
Forbici		
Pettine		
Spazzolino da denti		
Coltello senza forchetta		
Cucchiaio		
Martello		
Cacciavite		
Racchetta da tennis		
Coltello con forchetta		
Impugnare una scopa (mano superiore)		
Impugnare un rastrello (mano superiore)		
Accendere un fiammifero		
Svitare un coperchio		
Distribuire le carte		
Infilare un ago (mano che si muove)		
Calciare un pallone		
Totale		

Calcolo: **(dx – sx) / (dx + sx)**

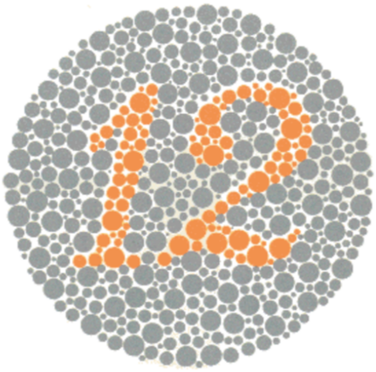
Mancini: -1 e 0,5

Ambidestri : - 05 e 0,5

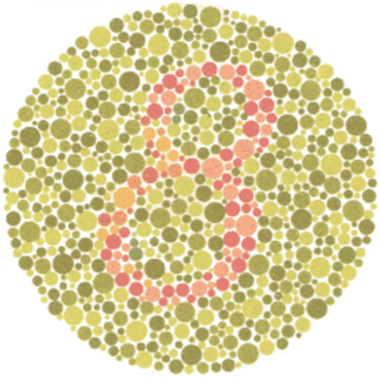
Destrimani: 0,5 e 1

H) Examples Ishihiara tables (1974)

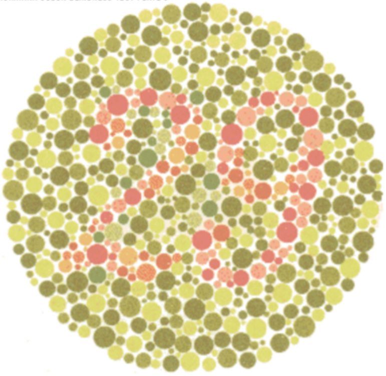
ISHIHARA COLOR BLINDNESS TEST PLATE 1



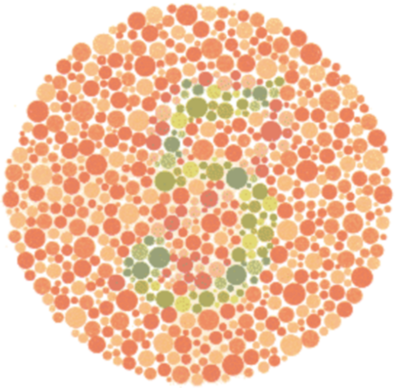
ISHIHARA COLOR BLINDNESS TEST PLATE 2



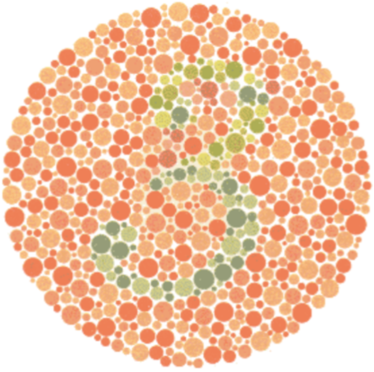
ISHIHARA COLOR BLINDNESS TEST PLATE 3



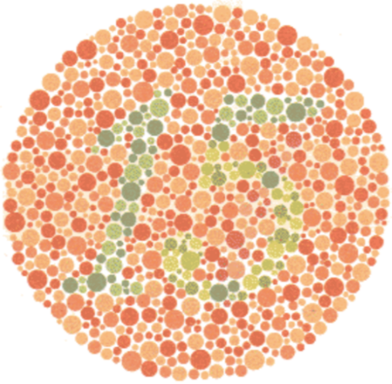
ISHIHARA COLOR BLINDNESS TEST PLATE 4



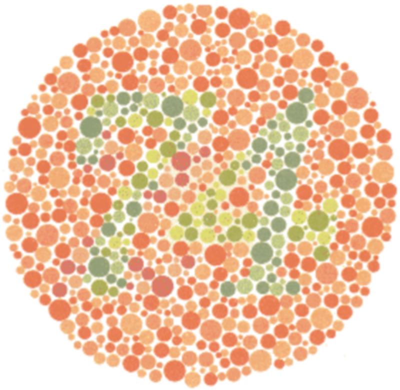
ISHIHARA COLOR BLINDNESS TEST PLATE 5



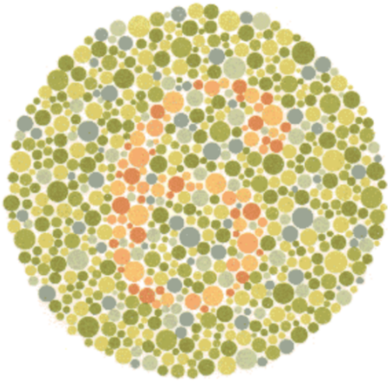
ISHIHARA COLOR BLINDNESS TEST PLATE 6



ISHIHARA COLOR BLINDNESS TEST PLATE 7



ISHIHARA COLOR BLINDNESS TEST PLATE 8



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