Syntax matters in shaping sensorimotor activation driven by nouns

Syntax matters in shaping sensorimotor activation driven by nouns

Gioacchino Garofalo[1,2*], Elena Gherri[1,3], Lucia Riggio[2]

[1] University of Bologna, Department of Philosophy and Communication, Via Azzo Gardino 23, 40122, Bologna, Italy

[2] University of Parma, Department of Medicine and Surgery – Unit of Neuroscience, Via Volturno 39, 43125, Parma, Italy

[3] University of Edinburgh, Department of Psychology - Human Cognitive Neuroscience - Edinburgh, UK

***Corresponding Author**

Gioacchino Garofalo

Department of Philosophy and Communication,
Via Azzo Gardino 23,
40122, Bologna, Italy
E-mail: gioacchino.garofalo@unibo.it

Keywords
Nouns; adjectives; sensorimotor simulation; syntax-semantic interplay; embodied cognition.

Abstract

Existing evidence has shown that adjectives modulate the grasp compatibility effect elicited by object nouns. The aim of the present study was to investigate the role of syntax on the sensorimotor activation elicited by nouns in a grasp compatibility task. We assessed two languages with different syntactic rules, Italian in Experiment 1 and English in Experiment 2. In both experiments, an adjective-noun pair was shown on the screen. The adjective was always in pre-nominal position and denoted either a disadvantageous quality of the object graspability (e.g., sharp) or the object colour (e.g., reddish). Participants had to categorize the object nouns as natural or artifact, performing a precision or a power reach-to-grasp movement. On different trials, the grasp response was compatible or incompatible with the grip typically used to manipulate the object indicated by the noun. In Experiment 1 (Italian language) the adjective-noun order violated the syntactic order and no difference emerged between reaction times on compatible and incompatible trials (no grasp compatibility effect). In Experiment 2 (English language), the adjective-noun order followed the syntactic rule. Results showed a grasp compatibility effect when a colour adjective was presented before a natural object noun. When a disadvantageous adjective preceded an artifact or a natural object noun, an inverted grasp-compatibility effect emerged with slower responses on compatible than incompatible trials. Taken together, these findings suggest that adjectives can shape the sensorimotor activation elicited by nouns of graspable objects, only when the syntax is correct. Results are discussed with respect to embodied cognition theories.

1. Introduction

Connections between action and perception have been widely demonstrated in many studies using the grasp compatibility task (e.g., Bub & Masson, 2010; Ellis & Tucker, 2000; Grèzes et al., 2003; Makris et al., 2011; Rounis et al., 2018; Vainio et al., 2008). This task requires participants to categorize an attribute of an object by performing a power or a precision grip. Typically, participants' performance improves when the response grip is compatible with the movement usually performed to interact with the size/shape of the object (compatible trials), whereas it worsens when the response grip is incompatible with the size/shape of the object (incompatible trials). The difference in performance between incompatible and compatible trials is called the grasp compatibility effect. Recently it has been demonstrated that the grasp compatibility effect can also be evoked by the nouns of graspable objects (e.g., Ferri et al., 2011; Glover et al., 2004; Gough et al., 2012; Marino et al., 2014; Tucker & Ellis, 2004). Thus, similarly to what observed for visually presented objects, also the semantic processing of objects nouns can recruit motor activity.

These evidence are in line with the general view of embodied cognition according to which the comprehension of language is grounded in the perceptual, motor and emotional systems (Barsalou, 2008; Borghi & Cangelosi, 2014; Buccino et al., 2016; Gallese & Lakoff, 2005; Martin, 2016; Pulvermüller & Fadiga, 2010). According to this perspective, the meaning of language is fundamentally rooted in our experiences and the re-enactment of sensorimotor systems is necessary for its understanding (Gallese, 2008; Garofalo et al., 2022; Vigliocco et al., 2009). The linguistic constituents of specific grammatical categories, such as verbs and nouns, seem to be more effective than others in re-enacting the sensorimotor systems during language comprehension (e.g., Taylor & Zwaan, 2008; Marino et al. 2012). Focusing on nouns, several studies have extensively documented the activation of the motor system driven by nouns of manipulable objects (Bub & Masson, 2012; Cattaneo et al., 2010; Glover et al., 2004; Gough et al., 2012; Marino et al., 2013; Rueschemeyer et al., 2010; Santana & De Vega, 2013; Tucker & Ellis, 2004) demonstrating that pragmatic features of the object (e.g., the shape or the typical size) are re-enacted during semantic processing. The re-enactment has been suggested to take place via mental simulation processes of experiential traces in the brain (Barsalou, 2008; Del Maschio et al., 2022; Richter et al., 2009), shaped through one's interactions with objects (or with any kind of event in general). Nevertheless, the simulation can be extended beyond a single word (verb or noun) when words from other grammatical categories specify how the action is performed (i.e., the adverb) and/or how the object is made (i.e., the adjective) (Garofalo et al., 2021; Klepp et al., 2017; Lachmair et al., 2016; Sieksmeyer et al., n.d.; Taylor & Zwaan, 2008; Zwaan & Taylor, 2006).

The first evidence for a sensorimotor involvement during the comprehension of the meaning of adjectives came from a TMS study (Gough et al., 2013). Single pulses were delivered to the participants' hand sector of the motor cortex, when they read adjectives denoting positive/manipulative or negative/disadvantageous pragmatic properties (e.g., soft or thorny, respectively). Motor Evoked Potentials were recorded from two antagonistic muscles involved in avoidance and manipulative actions, respectively. Results showed that muscle activity was differentially modulated by the meaning of the adjectives depending on the muscle function. The authors suggested that this modulation of the motor system reflected the motor experience associated with the adjectives during the acquisition of language. It is conceivable that the meaning of the adjective includes all the instances in which an individual interacted with a variety of referents (objects) sharing similar characteristics. When individuals process the adjective meaning, they also re-enact these interactions, learned and generalized throughout their lifespan.

Recent evidence complements these considerations by suggesting that the meaning of adjectives can modulate the sensorimotor activation evoked by the nouns of specific graspable

objects. In Garofalo et al. study (2021), a pair of words, including a noun followed by an adjective, was presented on each trial. Participants were asked to categorize a noun as either a natural object or an artifact, performing a reach-to-grasp movement (either precision or power grasp), compatible or incompatible with the grasp typically used to manipulate the objects to which the nouns referred to (i.e., grasp compatibility task). Results showed the presence of a grasp compatibility effect when the object noun was presented together with an adjective referring to a manipulative characteristic of the object, such as its shape (e.g., round) or its tactile properties (e.g., soft). By contrast, the grasp compatibility effect was not elicited when the object noun was associated with a '*disadvantageous*' adjective, which limited or prevented the typical grasping interactions with that object due to its potentially harmful characteristic (e.g., rotto, *broken*; tagliente, *sharp*). Interestingly, also adjectives denoting colours were effective in eliciting the grasp compatibility effect. This effect emerged only when colour adjectives were presented in combination with a natural object noun, suggesting that colour could convey relevant information for motor interactions at least for natural objects (e.g., the degree of ripeness of a fruit, see also Garofalo et al., 2022). Overall, when a motorically relevant characteristic of the object is made explicit by the adjective, the meaning of the adjective is integrated in the sensorimotor representation of the noun, modulating the motor system engagement (Garofalo et al., 2021). To summarize, object nouns can drive the sensorimotor simulation taking into account the object features which determine how it is grasped (e.g., the prototypical size or shape of the object). When an adjective is presented with the noun, specifying an additional property of the object, it can contribute to the motor simulation and can be relevant for the action selection process. It is therefore important to investigate how combinations of words from different grammatical categories (e.g., noun + adjective) contribute to the motor simulation process elicited during language comprehension.

Thus far, the only study investigating the impact of noun and adjective combinations on motor simulation have presented a noun followed by one adjective (e.g., Garofalo et al., 2021), according with the typical syntax order of the Italian language (Serianni, 1989). Therefore, the evidence of the modulation of the grasp compatibility effects observed for different categories of adjectives are limited to the correct syntactical presentation of these word pairs.

The position of the adjective with respect to the noun changes syntactically and morphologically in different languages. For example, in the Romance languages (e.g., French, Spanish, Portuguese, etc.) the adjective is typically presented in post-nominal position, whereas in Germanic languages (e.g., German, English), this order is typically inverted with adjectives in pre-nominal position. Since the syntactical combinatorial rules of a particular language are learned early during lifespan along with the semantic of words, it is conceivable that syntax could be also embedded in the sensorimotor processes that allow us to attributing meaning when we understand language. Accordingly, it has been proposed that these learned rules could have also an equivalent in the activation of the sensorimotor circuits engaged during the sensorimotor processing of words (Kemmerer, 2022; Pulvermüller & Fadiga, 2010; Roy & Arbib, 2005). Thus, syntax could play an important role since we learn the use of words in a certain order, as the result of repeated experiences of combining words in a sentence.

These considerations raise the question of the role of the linguistic experience of adjective placement within the noun-adjective pairing, that is, the role of the syntax in the sensorimotor processing of these word pairs. To evaluate the impact of syntax on the semantic processing of noun-adjective combinations, we carried out two experiments in which participants had to categorize nouns of graspable objects as artifact or natural, by performing a reach-to-grasp action (i.e., reach-to-grasp compatibility task). In both experiments the adjective (either a colour or a disadvantageous one) was presented before the noun in pre-nominal position. In Experiment 1, which was carried out in the Italian language (with Italian speaking participants), this adjective-noun

order violated the syntactic rule of the language, while in Experiment 2, carried out in English (with English speaking participants), the adjective in pre-nominal position met the principles governing the word order in this language.

If the integration of the adjective meaning with the sensorimotor representation of the noun is syntax-independent, we expect a replication of previous results in both experiments (Experiment 1 and Experiment 2), with fine-tuned modulations of the grasp compatibility effects regardless of the adjective placement. This pattern of results would suggest that syntax and semantics are differentially elaborated, and that syntax does not affect sensorimotor activation.

On the other hand, if the integration is syntax-dependent, we expect a different pattern between results of Experiment 1 and 2. When the syntax is violated (Experiment 1), the meaning of adjective and noun are not integrated, and the sensorimotor simulation could be exclusively driven by the noun regardless of the adjective category it is paired with. This should lead to similar grasp compatibility effects across conditions. In contrast, when the syntax rules are met (Experiment 2), the meaning of the different categories of adjectives should modulate the sensorimotor activation driven by nouns. This pattern of results would suggest that there is an interplay between syntax and semantics on the sensorimotor activation.

2. Experiment 1

In Experiment 1, we asked a group of Italian participants to perform a reach-to-grasp compatibility task. We presented on the screen two Italian words, one adjective followed by one object noun, and participants had to categorize the noun as natural or artifact by performing a precision or power grasp movement. In the original study of Garofalo and colleagues (2021), the noun was presented before the adjective, following the correct syntactic rule. In the present experiment the adjective-noun order violated the correct order of presentation. This manipulation represents a first attempt to investigate the role of syntax in the sensorimotor processes of language. If adjective and noun are integrated regardless of the incorrect syntax order, we expect a pattern of results similar to that observed in Garofalo et al. (2021). That is, we expect a grasp compatibility effect when the colour adjectives precede natural object nouns, but not when they are combined with artifact nouns. Disadvantageous adjectives should lead to a reduction/suppression of the grasp compatibility effect for both object categories, according to the hypothesis that integration is syntax-independent. By contrast, if the integrative process between noun and adjective is syntax-dependent, the syntax error may result in the disruption of the sensorimotor integrative processing of the adjective-noun combination, leading to a grasp compatibility effect driven by nouns since they are read as second word.

2.1. Methods

2.1.1. Sample size estimation

We conducted an a-priori power analysis to determine the adequate sample size. We used previously published data from our lab (Garofalo et al., 2021, - Experiment 2), obtained with the same reach-to-grasp compatibility task. To determine the sample size, we used the means of trimmed and transformed back data of 26 participants related to the significant three-way interaction (Object category X Adjective X Grasp compatibility). The observed power was about 99% for 26 participants in Experiment 2 of Garofalo et al. (2021). Here, we assessed the minimum sample size needed to detect 80% of power involving the same effect size as in Garofalo et al. (2021, Exp. 2). Power analyses were performed using the simr package in R (Green & Macleod, 2016), simulating and then modelling 1000 independent experiments with increasing numbers of participants. Power

analyses results showed that the minimum sample size ranged between 14 (Power: 77.80%, 95% CIs = 75.10% - 80.34%) and 16 participants (Power: 84.40%, 95% CIs = 82.00% - 86.66%). We chose 18 participants (Power: 90.50 %, 95% CIs = 88.51% - 92.25%) for both experiments since this number of participants allowed us to control for possible drop-out or exclusion of participants.

2.1.2. Participants

Eighteen participants (10 females; mean age in years = 20.8 ± 2.4 SD) volunteered to take part in the experiment at the University of Parma. 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 of them were 18 years old, or older, at the time of the study and naïve as to the purpose of the experiment. Prior to participation, each participant gave her/his informed consent, in accordance with the ethical standards of the Declaration of Helsinki. The research was conducted in accordance with the ethical standards of the Italian Board of Psychologists (http://www.psy.it/codice_deontologico.html) and of the Italian Psychological Society (AIP, see http://www.aipass.org)

2.1.3. Task

Participants were asked to categorize the noun presented in an adjective and noun combination as natural or artifact. To ensure that participants processed the whole noun-adjective combination, three different categories of adjectives were used (colour, disadvantageous and human quality adjective). When the adjective denoted a color or a disadvantageous property of the object (reach trials), participants were asked to perform either a precision or a power reach-to-grasp movement toward a custom-made response device with their right hand (see Figure 1), as indicated by the instructions (e.g., power grasp = natural objects and precision grasp = artifact or viceversa). When the adjective denoted a human quality (catch trials, e.g., arrogant cup), participants had to refrain from performing any reach-to-grasp movements. In this case, they were instructed to lift their right hand and replace it in the initial position. The introduction of catch trials forced participants to read not only the nouns but also the adjectives to perform the task correctly. The response grasp on reach trials was either compatible or incompatible with the grasp movements normally used to manipulate the objects denoted by the nouns. The mapping between the noun category (natural or artefact objects) and the required response (power or precision grasp) was counterbalanced across participants. On all trials (both reach trials and catch trials), the stimuli disappeared from the screen when the participants lifted their hand.

2.1.4. Apparatus, Procedure and Stimuli

The experiments took place in a sound-attenuated and dimly illuminated room. The experimental apparatus consisted of a 42'' (Experiment 1) or 24'' (Experiment 2) 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 consisted of three parts: two wood cylinders placed on top of each other and a squared starting base (10 cm × 10 cm). The dimension of the bottom cylinder was compatible with a power grasp (power cylinder: h = 14 cm, d = 6 cm), while the dimension of the top cylinder was compatible with a precision grasp (precision cylinder: h = 4 cm, d = 1.5 cm). The cylinders were placed 43 cm from the chin-rest. The starting base was located centrally with respect to participants' body midline (see Figure 1). All the three parts of the response device were connected to an external USB device trigger through three separate capacitive sensors. The three device parts allowed us to measure the Reaction Times (RTs; time between the onset of the visual stimuli and the onset of the hand movement) and the Movement Time (MTs) for precision and power reach-to-grasp

movements (time between the hand movement onset and the grip of one of the two manipulanda (for similar task see Bub & Masson, 2010; Makris et al., 2013; Symes et al., 2008). The RTs and the MTs are related to the planning and the execution (or actualization) of the movement, respectively (Castiello, 1999, 2005; Glover, 2004; Jeannerod, 1984).

Each trial started when the participant placed the palm of her/his right hand on the starting base. The device did not require pressure to detect the presence of the hand. In this way, it was possible to avoid the activation of hand or arm muscles, reducing 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 in the centre of the screen. The cross remained on the screen for a variable duration, randomly selected between 500 and 1000 ms, to avoid habituation**.** After this variable interval, two words (the adjective followed by the noun**,** see supplementary materials for the lists of words combination) replaced the fixation cross and remained on the screen until the hand was lifted from its resting position. Both adjective and noun appeared on the same string in the center of the screen (1920 × 1280 resolution) in white characters on a black background (bold courier new, 24-point size).

Stimuli were adapted from Garofalo and colleagues' study (2021) and included thirty-two Italian object nouns: 8 nouns referring to natural objects, graspable with a precision grip (e.g., oliva, olive), 8 referring to natural objects, graspable with a power grip (e.g., 'patata', potato), 8 referring to artifacts, graspable with a precision grip (e.g., 'chiodo', nail) and 8 referring to artifacts, graspable with a power grip (e.g., 'bottiglia', bottle). Following the procedure used by Garofalo and colleagues (2021) relative to the validation of pairings of objects nouns and disadvantageous adjectives combinations, color adjectives paired with objects nouns used in the present study were also validated. Results are reported in the Supplementary materials (Sassenhagen & Alday, 2016)**.** Each noun was presented with one adjective selected from 8 possible different adjectives denoting a disadvantageous quality (e.g., 'tagliente', sharp) and 8 different adjectives denoting the colour of the object, with a total of 64 combinations. Half of them referred to objects typically grasped with power grip, the other half to objects typically grasped with precision grip. There were also 16 catch combinations consisting of one of the nouns used as stimuli and an adjective denoting a human quality (e.g., 'oliva emotiva', emotive olive). Each noun-adjective combination presented on reach trials was repeated randomly eight times, while catch combinations were randomly presented four times. Total trials were 576. All these stimuli were validated in our previous study (see Garofalo et al., 2021 – Appendix S1).

The experimental task started after a practice session of 40 trials. Participants were tested individually, and they were instructed to find the best compromise between speed and accuracy while performing the task.

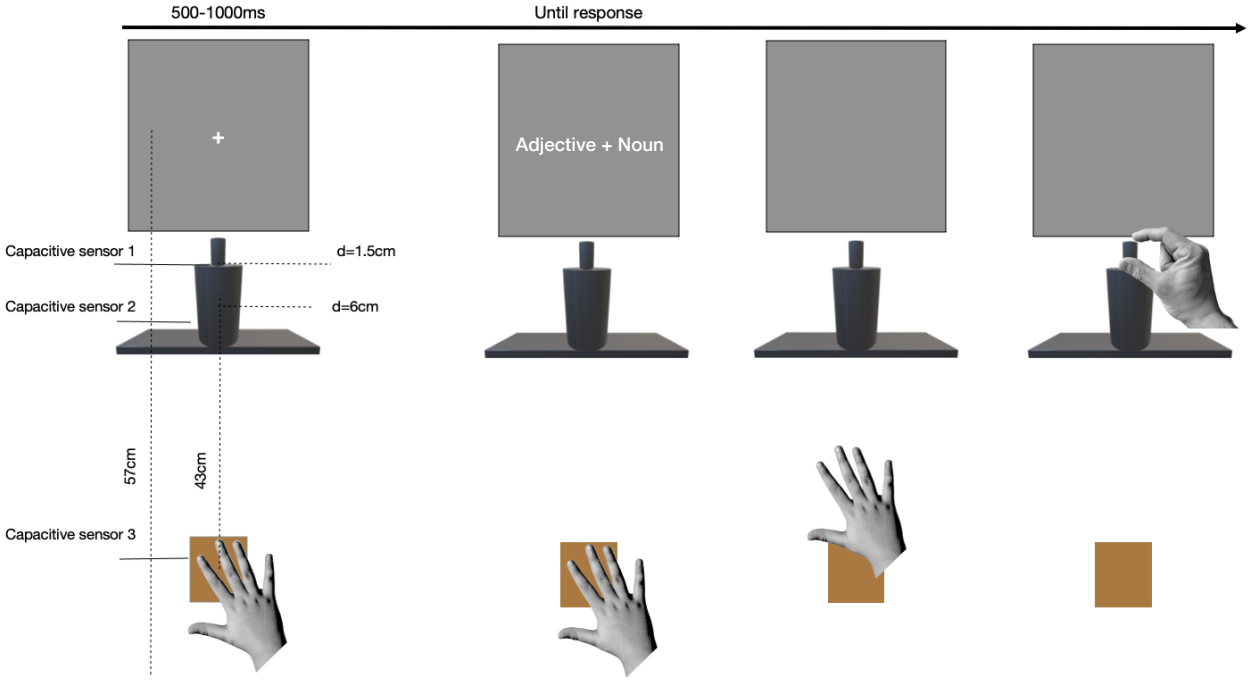

Figure 1. Representation of the experimental setup and the sequence of events**.**

2.1.5. Analyses

Data analyses were performed using R 4.0.0 (R Core Team, 2020). Participants' errors were checked and excluded from further analyses. RTs and MTs were analysed by first removing practice, catch trials, datapoints indicative of anticipatory responses (< 150 ms) and outliers. Outliers were detected inspecting the RTs distribution to evaluate deviations from normality (see Figure 2). When visual inspection of these residual data showed a marked deviation of the sample quantiles distribution from the theoretical quantiles, we assessed whether these values were outliers using the Leys' method (Leys et al., 2013) applied to the residual of the theoretical distribution (see also Britt et al., 2016). We excluded from the analysis responses that exceeded three times this criterion.

Both for RTs and MTs trimmed data, we checked the distributions and whenever they showed a marked deviation from normality, we applied an iterative Box-Cox procedure (Box & Cox, 1964; Klein Entink et al., 2009) to find the transformation that best yielded data. All data and confidence interval limits reported in the manuscript were transformed back to ms by computing the inverse of the transformation.

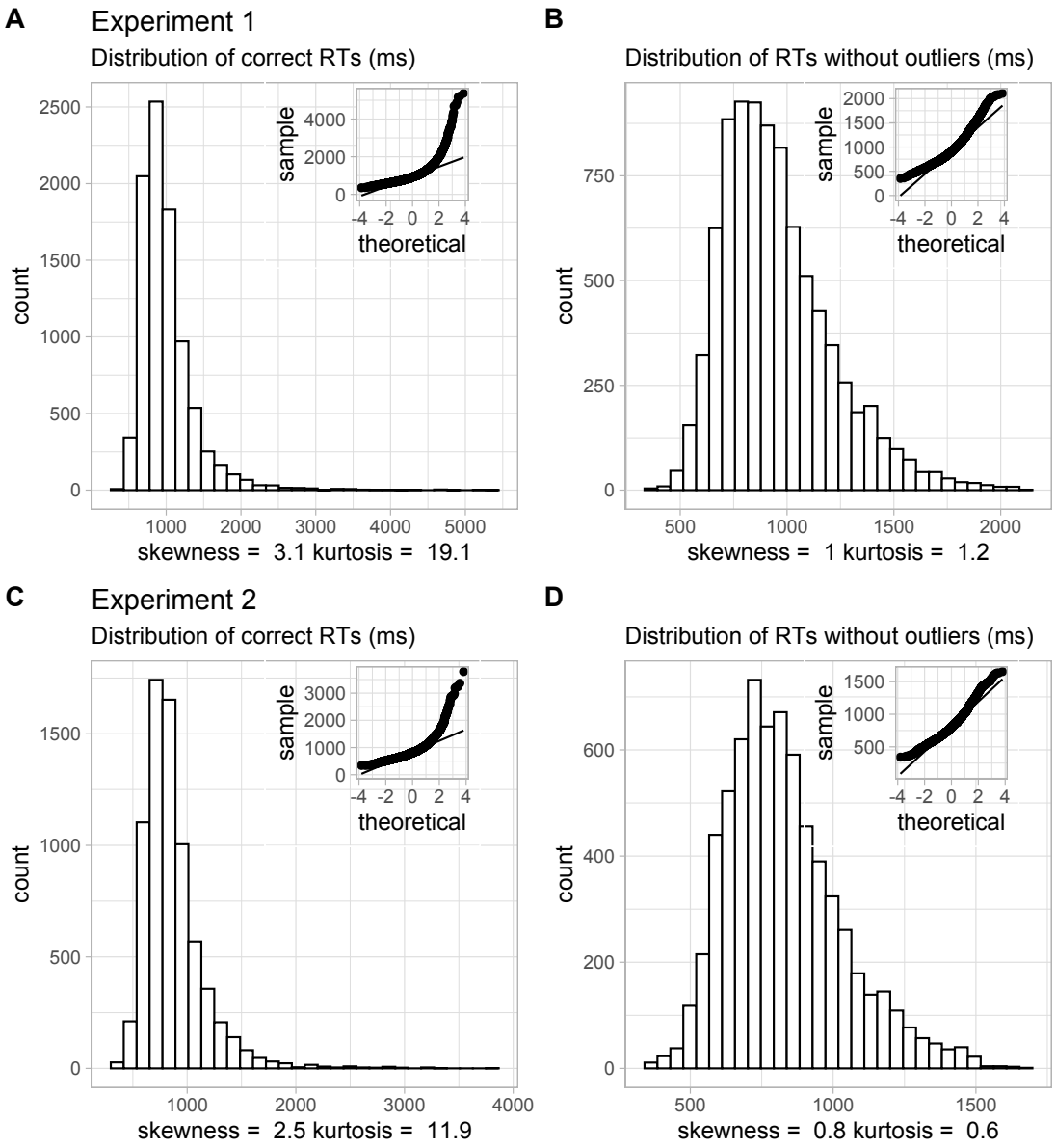

Figure 2. RT distributions in Experiments 1 and 2. The upper panels (A and B) show the RT distribution in Experiment 1 with associated normal Q-Q plots (inset graphs). In the bottom panels (C and D), the distribution of RTs in Experiment 2 is shown, as well as the normal Q-Q plots. Below the distribution graphs the values of skewness and kurtosis are indicated.

Separate analyses were carried out on RTs and MTs recorded on accurate reach trials. Due to the design of the experiment – with multiple observations for each participant – and in agreement with the current recommendations in psychology and behavioural neuroscience (Barr et al., 2013; Cumming, 2014; Kline, 2004; Matuschek et al., 2017), we performed the analysis on RTs and MTs using Linear mixed model (LMM). We included in the model the fixed effects of Grasp compatibility (2 levels: compatible and incompatible), Object category (2 levels: natural and artifact) and Adjective (2 levels: colour and disadvantageous) as well as their interactions. Furthermore, participants and stimuli were set as random effects. Models were computed using the lmer() function of lm4 package (Bates et al., 2015).

2.1.6. Results

Error rates were less than 5% of the total number of trials (218 datapoints, data loss = 2.37%) and were not analysed further. Inspection of catch trials revealed that participants performed the experiment accurately, making 64 errors (participants did not respond) over 1152 total catch trials (5.5%). Considering the RTs on reach trials, no anticipatory RTs were detected. We also removed 381 outliers (data loss = 4.23%). After data trimming procedure, RTs data showed kurtosis = 1.2 and skewness = 1 (see Figure 2 – A and B). With these values no further transformation was applied. The RTs model did not show any reliable fixed effects or interactions (see Figure 3A). MTs distribution was checked, and it showed a marked deviation from normality. MTs were transformed using lambda = 0 (Logarithmic transformation) to reduce skewness and kurtosis of the distribution. The analysis of MT logarithmic data did not show any reliable effect (see Figure 3B).

Although no reliable effects emerged for the RT and MT analyses, there was a statistical trend for the grasp compatibility main effect in both RTs and MTs analyses (RTs: Estimate = |12.17|, t = |1.48|, p = 0.14; MTs: Estimate = |7.86|, t = |1.86|, p = 0.06, see also Figure 3), with faster compatible (RTs: Mean = 947 ms, Std.Dev. = 254.41, Std.Err. = 3.88; MTs: Mean = 395 ms, Std.Dev. = 66.28, Std.Err. = 15.62) than incompatible responses (RTs: Mean = 954 ms, Std.Dev. = 259.17, Std.Err. = 3.95; MTs: Mean = 401 ms, Std.Dev. = 63.43, Std.Err. = 14.95).

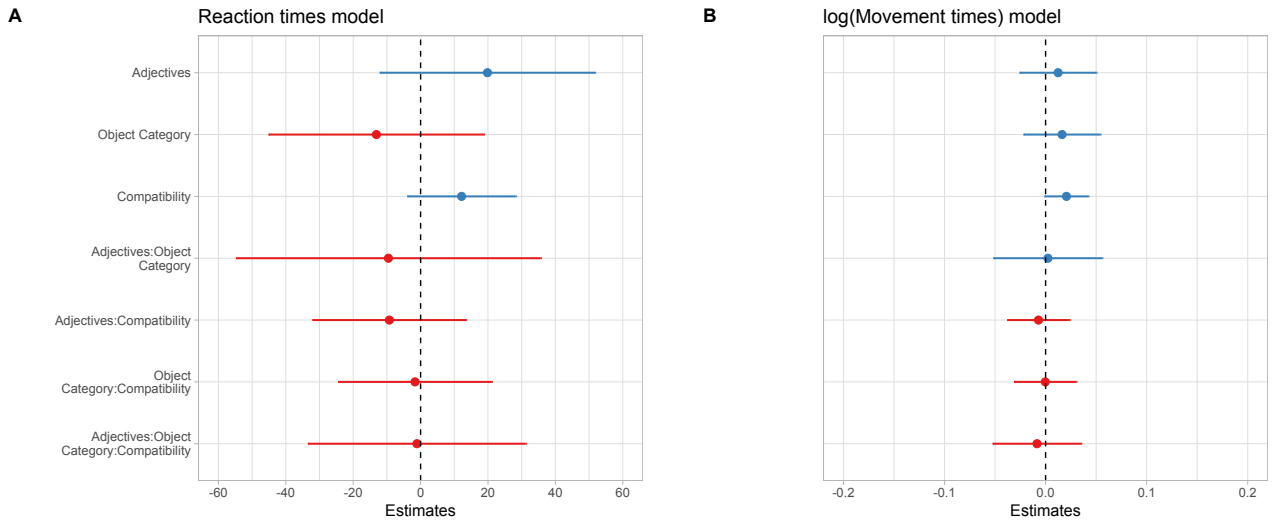

Figure 3. Forest plots for the RTs and log(MTs) analyses of Experiment 1. On the x-axes are reported the estimates fixed effects. On the y-axes the factors of the models are reported. The dotted lines indicate the absence of the effect, while the red color refers to effects below 0 and blue color refers to effects above 0. The dots indicate the fixed effects estimated by the model with the associated 95% CIs.

2.2. Discussion

The results of the present experiment showed that the grasp compatibility effect was not statistically reliable when the adjective was presented in pre-nominal position, neither as main effect nor in interaction with object category and/or adjectives. This finding is surprising because the grasp compatibility effect has been replicated in several studies with nouns of graspable objects (e.g., Ferri et al., 2011; Glover et al., 2004; Gough et al., 2012; Marino et al., 2014; Tucker & Ellis, 2004), and also with specific combinations of adjectives and nouns (Garofalo et al., 2021). The absence of the grasp compatibility effect modulation by adjectives clearly rules out the syntax-independent hypothesis, that is the possibility that analogous grasp compatibility effects are triggered by the presentation of adjective and noun combinations regardless of their order of presentation. By contrast, these findings seem to support the syntax-dependent hypothesis.

Intriguingly, we had originally hypothesised that when the syntax rules are not met, the adjectives meaning is not integrated in the sensorimotor representation of the noun, leading to the presence of an overall grasp compatibility effect driven by the nouns similar across adjective categories. However, results suggest an even more extreme effect of syntax violation on the grasp compatibility effect elicited by the noun, as indicated by the fact that breaching the syntactic rule led only to a statistical trend for the compatibility effect. Indeed, incompatible responses were slightly slower than compatible ones both in the planning phase (RTs) and movement phase (MTs), without any modulation by adjectives. Thus, it is possible that nouns can still elicit a residual motor program when they are read as the second word in the adjective-noun combinations.

While the pattern of results observed in Experiment 1 is consistent with a role of syntax in the sensorimotor integration of noun and adjective combinations, it is also consistent with an explanation based on the relative position of adjective and noun. One could argue that the modulations of the grasp-compatibility effect observed in the original study by Garofalo et al., (2021) with different types of adjectives could have been driven by the relative position of noun and adjective. That is, the sensorimotor circuits responsible for the grasp compatibility effect were initially activated by the noun (the first word), which is the verbal referent of a graspable object, and subsequently modulated by the mere presence of the adjective in post-nominal position. For example, a disadvantageous adjective could lead to the reduction of the grasp compatibility effect driven by the noun because it denotes a potentially harmful feature which halts the sensorimotor activation. In the present Experiment, when the adjective is read as the first word of the combination, its meaning does not affect the grasp compatibility, and the noun entirely drives the simulation leading to similar effects across conditions.

Italian speakers generally use a noun–adjective word order. Thus, placing the adjective in pre-nominal position not only breached the typical syntactic order for noun-adjective pairings but also altered their relative position. It is therefore possible that the (lack of) results observed in the present experiment is driven by the specific order of adjective and noun rather than the violation of their syntactic order. To disentangle between these two hypotheses, we performed a second experiment in a different language in which the syntactic order of noun and adjective is naturally inverted as compared to Italian.

3. Experiment 2 – English

In Experiment 2 we carried out a conceptual replication of the study by Garofalo and colleagues (2021) in the English language in which adjectives are usually placed before the nouns.

This manipulation will allow us to compare the effect of the adjective in pre-nominal position, when the syntactic rule of adjective-noun placement is met. If the adjective-noun integrative process is *syntax-dependent*, when the adjective is presented before the noun, we expect to replicate the pattern of results previously observed in Italian (Garofalo et al., 2021) also in the English language. Specifically, the grasp compatibility effect should emerge with colour adjectives when these are combined with natural but not artifact objects nouns. In addition, the grasp compatibility effect should be reduced/eliminated when natural and artifact objects nouns are combined with disadvantageous adjectives. Alternatively, if findings of Experiment 1 are the consequence of a mere *positional effect* (adjective before the noun), we expect a similar grasp compatibility effect across different adjective types. When the adjective is read as the first word of the combination, the meaning of the adjective is not integrated in the sensorimotor representation of the noun. In this situation, the noun alone drives the sensorimotor simulation, and the adjective meaning does not affect the grasp compatibility.

3.1. Method

3.1.1. Participants

Eighteen students from the University of Edinburgh (8 females; mean age = 23.8 ± 2.4 SD) were enrolled and rewarded with a credit course. All participants were right-handed (Oldfield, 1971) and had normal or corrected-to-normal vision. We excluded one participant from further analyses due to difficulties in understanding the task. All participants were naïve as to the purpose of the experiment and gave their informed consent prior to participation. The experiment was conducted in accordance with the Declaration of Helsinki and received approval from the PPLS ethics committee of the University of Edinburgh (Ethics Approval Code: 161-1819/1).

3.1.2. Stimuli

As in Experiment 1, the stimuli consisted of two words, an adjective and a noun, presented in the correct syntactic order for the English language (i.e., adjectives followed by nouns). The list of combinations of adjectives and nouns used in the present study was translated and adapted from the stimuli used in the study by Garofalo et al. (2021) with the help of a native English speaker. Some of the original combinations were replaced because they were not adaptable to the English language (stimuli are reported in the supplementary section). These new combinations were further validated by an independent group of participants and results are reported in the Supplementary materials. Twenty-eight nouns were used: 7 nouns referring to natural objects graspable with a precision grip (e.g., olive), 7 referring to natural objects graspable with a power grip (e.g., potato), 7 referring to artifact objects graspable with a precision grip (e.g., nail), 7 referring to artifact objects graspable with a power grip (e.g., bottle). As in Experiment 1, each noun was associated either with a disadvantageous or a colour adjective in different trials, for a total of 56 combinations. Each adjective + noun combination was presented eight times, for a total of 448 *reach trials*. To make sure that participants read both the adjective and the noun in the combination presented on the screen, we added 14 control combinations (catch trials). Each control combination consisted of one noun preceded by an adjective denoting a human quality (e.g., emotive olive). Each of the 14 adjective + noun combination for catch trials was presented four times, for a total of 56 *catch trials*. Thus, the experiment consisted of 504 trials in total.

3.2.3. Analyses and Results

Analyses followed the same procedure described for Experiment 1. Error rates were less than 5% of the total number of trials (354 errors, 4.65%) and were not further analysed. Inspection of the catch trials revealed that participants' accuracy was extremely high, with a total of 12 errors out of 1008 total catch trials (1.2%) across all participants. Considering the RTs on reach trials, we further excluded 345 datapoints (data loss = 4.75%) considered outliers. Trimmed RTs showed kurtosis = 0.6 and skewness = 0.8 (see Figure 2 – C and D) and no further transformation was applied.

The RTs analysis showed a reliable fixed effect of Grasp compatibility (Estimate = |19.37|, t = |2.52|, p = 0.012), with faster RTs for incompatible condition (Mean = 824 ms, Dev.Std. = 199.72, Err.Std. = 3.43) as compared to compatible one (Mean = 831 ms, Std.Dev. = 204.82, Std.Err. = 3.45). The fixed effect of Adjective was also reliable (Estimate = |27.84|, t = |2.22|, p = 0.029), showing faster RTs for colour adjectives (Mean = 815 ms, Std.Dev. = 204.82, Std.Err. = 3.45) as compared to disadvantageous ones (Mean = 841 ms, Std.Dev. = 196.38, Std.Err. = 3.23). Finally, the interaction of interest between Grasp compatibility, Adjective and Noun category was reliable (Estimate = |38.55|, t = |2.53|, p = 0.011). This revealed that the presentation of a disadvantageous adjective before a natural or artifact object noun resulted in slower RTs on compatible compared to

incompatible trials, and that the presentation of a colour adjective before a natural object noun generated the classical grasp compatibility effect, with faster responses on compatible than incompatible trials. Finally, as expected, the data showed similar response times between compatible and incompatible responses when artifact nouns were presented in combination with colour adjectives. Planned comparisons testing the statistical significance of the grasp compatibility effect are reported in full in the supplementary materials and are summarized in Table 1. Descriptive statistics of the three-way interaction are presented in Table 1 and Figure 4.

		Compatible			Incompatible			Grasp compatibility
		mean	std.dev.	std.err.	mean	std.dev.	std.err.	
artifact	Disadvantageous	857	217.30	7.40	831	204.57	7.07	-26 *
	Colour	826	208.69	7.00	819	197.95	6.83	-7
natural	Disadvantageous	851	204.63	6.86	824	201.36	6.96	-27 *
	Colour	792	181.33	6.07	821	195.22	6.62	29 *

Table 1. Descriptive statistics of Experiment 2. Grasp compatibility is calculated as the difference between incompatible and compatible conditions. Statistical reliable contrasts ($p < 0.05$) are indicated with *.

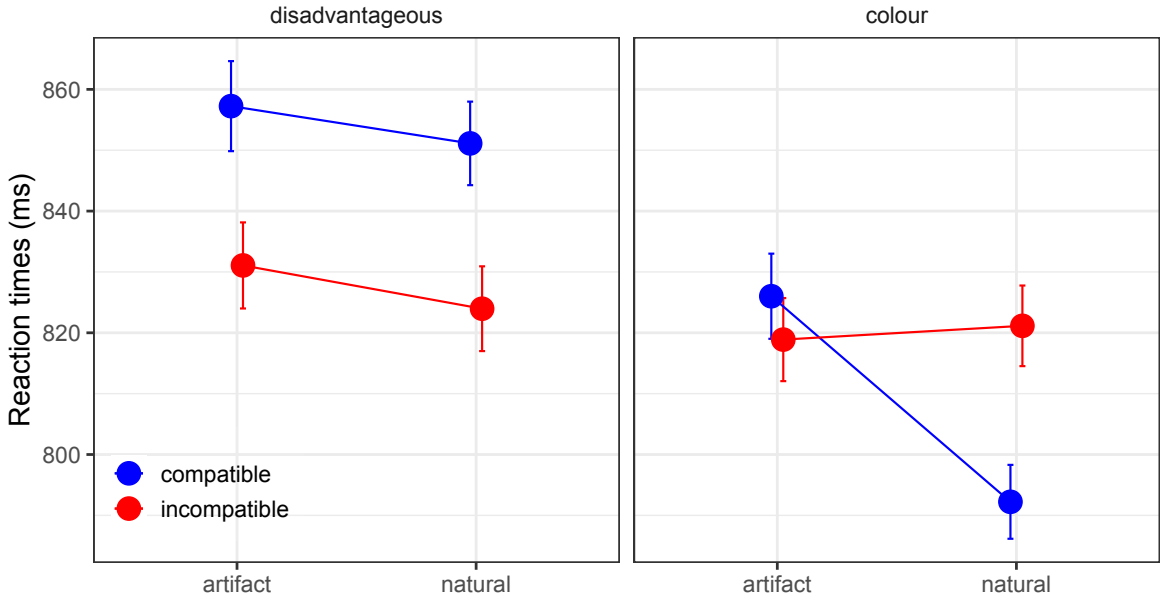

Figure 4. Averages values of RTs for Experiment 2 are shown as a function of the Object Category and Adjectives factors. Error bars represent the standard error of the means.

The inspection of MTs distribution showed a marked deviation from normality. Box-Cox iterative procedure suggested lambda = 0, hence MTs were logarithmic transformed. The analysis revealed a statistically reliable interaction between Grasp compatibility and Noun category (Estimate = |17.50|, t = | 2.60|, p = 0.009), showing that during the movement phase a grasp compatibility effect was present for natural object nouns (Compatible: Mean = 350 ms, Std.Dev. = 63.08, Std.Err. = 15.30; Incompatible: Mean = 364 ms, Std.Dev. = 50.70, Std.Err. = 12.30), but not for artifact nouns (Compatible: Mean = 362 ms, Std.Dev. = 53.44, Std.Err. = 12.96; Incompatible: Mean = 362 ms, Std.Dev. = 50.72, Std.Err. = 12.30).
For an overview of the results of both RT and MT models see Figure 5.

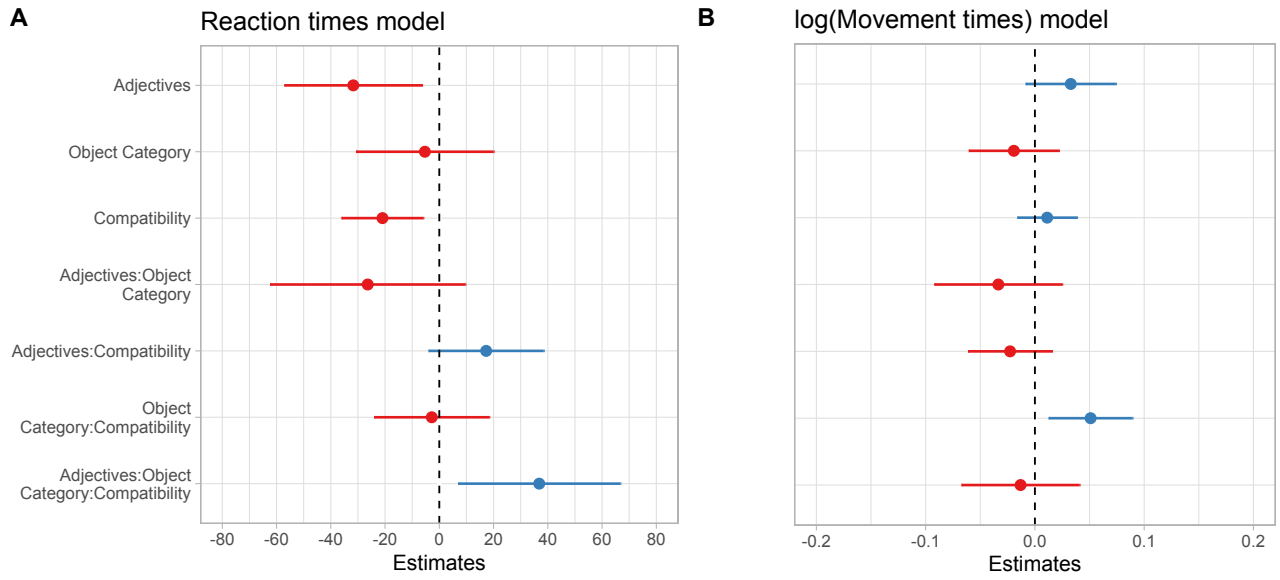

Figure 5. Forest plots for the RTs and log(MTs) analyses of Experiment 2. On the x-axes are reported the estimates fixed effects. On the y-axes the factors of the models are reported. The dotted lines indicate the absence of the effect, while the red color refers to effects below 0 and blue color refers to effects above 0. The dots indicate the fixed effects estimated by the model with the associated 95% CIs.

3.2. Discussion

The results of Experiment 2 in the English language clearly demonstrated that the sensorimotor simulation driven by the processing of the noun can be modulated by adjectives even when these are in pre-nominal position, largely replicating the findings originally reported by Garofalo and colleagues (2021) in Italian. This implies that the integrative process between noun and adjective is syntax-dependent. Experiment 2 results rule out both the possibility that the noun has to be presented first to observe a modulation of the grasp-compatibility effect, but also that the noun alone (as read after the adjective) drives the sensorimotor simulation, determining a grasp compatibility effect unaffected by the type of adjectives**.**

In detail, the analysis of RTs revealed the presence of a grasp compatibility effect elicited when colour adjectives were combined with natural nouns but absent when they were combined with artifact nouns (see Figure 4). The effect of colour adjectives combined with natural object nouns on motor activation further supports the hypothesis that colour information contributes to the sensorimotor representation of natural objects (Berndt et al., 2018; Hansen et al., 2006; Martin et al., 1995; Naor-Raz et al., 2003; Simmons et al., 2007; Therriault et al., 2009). Colour can convey motor-relevant information and this occurs mainly for natural objects, facilitating the interaction with these objects (Bompas et al., 2013; Garofalo & Riggio, 2022; Naor-Raz et al., 2003). The present finding closely matches what previously observed with the adjective in post-nominal position in the Italian language (Garofalo et al., 2021).

Furthermore, the presence of a disadvantageous adjective in pre-nominal position (regardless of noun category) resulted in an inverted grasp compatibility effect, with compatible responses slower than incompatible ones. Previous studies have shown that the presence of a broken handle (e.g., Buccino et al., 2009) or a dangerous object like a broken bulb (e.g., Anelli et al., 2012) disrupted the possibility to interact with these objects. In these cases, the automatic motor activation typically elicited by the intact object was reduced or eliminated when the conditions to act upon it were not met (e.g., Anelli et al., 2012; Buccino et al., 2009; Riggio et al., 2006). In line with this, the presence of the disadvantageous adjective before the object noun in the present experiment disrupted the motor simulation elicited by the noun, replicating previous evidence. Interestingly, the impact of

the adjective on sensorimotor activation appeared to be even stronger in pre-nominal position (Experiment 2 of the present study) compared to post-nominal position (Garofalo et al., 2021). Indeed, while the grasp compatibility effect disappeared with disadvantageous adjectives in post-nominal position (Italian, Experiment 2 Garofalo et al., 2021), an inverted compatibility effect was observed in the present study with the adjective pre-nominal position (English). The validation results ruled out the possibility that the grasp-compatibility effects observed were driven by items properties. As expected, validation data revealed that natural object nouns were more familiar in combination with colour adjectives as compared to artifact nouns combined with the same class of adjectives. This is due to the fact natural objects have prototypical colour (e.g., yellow banana) whereas artificial objects are manufactured with different colours, further suggesting a close relationship between colour properties and natural objects (Hansen et al., 2006).

The modulation of the grasp compatibility effects cannot be explained by differences in the frequency of use of the combinations of adjectives and nouns nor to difficulties in imaging the stimuli, since the results of the validation did not show any reliable differences. Furthermore, even if artifact nouns were rated as more graspable, when combined with colour adjectives this advantage disappear in the compatibility task. Finally, as expected, results of the explicit judgment task showed that disadvantageous adjectives reduced the graspability of the object which the noun referred to, regardless of the object category. This result is congruent with the results of the behavioral task.

The present results also revealed that the modulation of the adjective on the sensorimotor activation elicited by the noun affected mainly compatible responses. While disadvantageous adjectives slowed down compatible responses, leading to a negative compatibility effect, colour adjectives combined with natural object nouns resulted in faster compatible responses compared to all other conditions. These two effects can be interpreted as interference and facilitation on the compatible motor program. Previous studies (e.g., Glover et al., 2004; Marino et al., 2013) have suggested that accessing the meaning of an object noun activates the motor program(s) usually related to the interaction with the object (i.e., object affordances). In the present study, when the adjective was combined with the noun, the adjective was able to shape the sensorimotor activation driven by the noun in the direction of its meaning.

It is interesting to note that the grasp compatibility effect also manifests itself in the execution phase of the movement (MTs) but only for natural object nouns. Natural object nouns are not affected by the meaning of adjectives, with faster movements under compatible conditions with both disadvantageous and colour adjectives. Evidence for dissociative processes between action planning and its online control has been demonstrated with both visually presented objects and object nouns (e.g., Castiello, 1996, 1999; Gentilucci et al., 2000; Glover, 2004; Glover & Dixon, 2002). We speculate that the nouns presented after the adjectives were able to drive sensorimotor processes by themselves. The observation that a grasp compatibility effect was exclusively present for natural objects in the present experiment could be explained by the different types of motor interactions typically performed with natural and artifact objects. While artifacts evoke both manipulative actions and actions related to the use of the object, that do not necessarily coincide (Borghi & Riggio, 2015; Jax & Buxbaum, 2010), motor interactions with natural objects are mainly related to manipulation for grasping (Visani et al., 2021). In the language domain, stable affordances are typically re-enacted upon of words referring to manipulable objects (Borghi & Riggio, 2015; Sakreida et al., 2016). Specifically, artifact nouns mainly evoke motor programs characterized by objects function and use (Creem-Regehr & Lee, 2005; Gough et al., 2012; Rueschemeyer et al., 2010), whereas natural nouns elicit motor programs related to grasping, which are more closely related to the motor response required in this study (Visani et al., 2021). To sum up, the results obtained in the present study revealed that the meaning of the adjective has a direct effect on the

activation of motor programs elicited by the noun. The presence of the adjective in pre-nominal position in this study (with the English language) shaped the sensorimotor simulation in the direction of the meaning of the adjectives and affected the planning of the movement. Thus, the sensorimotor simulation elicited by the noun was active beyond the noun itself. This observation supports the presence of an integrative process combining noun and adjective into larger information units.

3.3 Results comparisons

In order to evaluate the impact of syntax rules on the sensorimotor modulation driven by adjectives, we compared results of Experiment 1 and 2 of the present study with those of Experiment 2 described by Garofalo and colleagues' study (2021), in which the words combinations followed the typical syntactic rule of Italian language. For all experiments, we calculated the grasp compatibility effect (i.e., Incompatibile RTs – Compatibile RTs) as a function of the two classes of adjectives (Colour and Disadvantageous) and Category of objects (Natural and Artifact) with the associated 95% CIs by discarding participant-by-participants variation (Morey, 2008). In this way, it is possible to compare the differences of the grasp compatibility effects observed with different object and adjective categories, different languages and different syntactic orders. Importantly, this method allows also to contrast the presence and absence of the grasp-compatibility effect.

As shown in Figure 6 (left panel), results revealed robust grasp-compatibility effects when a natural object noun was presented with a colour adjective (Experiment 2 present study - English and Experiment 2 Garofalo et al. 2021 - Italian) following the correct syntactic order. When, however, this syntactic order was incorrect (Experiment 1 present study – Italian) there was no grasp-compatibility effect when the natural object nouns were paired with colour adjectives. When artifact nouns were combined with colour adjectives (Figure 6 - left panel), results revealed the absence of grasp compatibility effects in all experiments. When object nouns were combined with disadvantageous adjectives (Figure 6 – right panel), no reliable positive grasp compatibility effect emerged in any of the study. It is worth noting that in English (Experiment 2 of the present study), an inverted grasp-compatibility effect emerged with disadvantageous adjectives.

Taken together these results support the hypothesis that syntax plays a relevant role in determining the presence and the size of the grasp compatibility effect as well as its modulation by the adjective category.

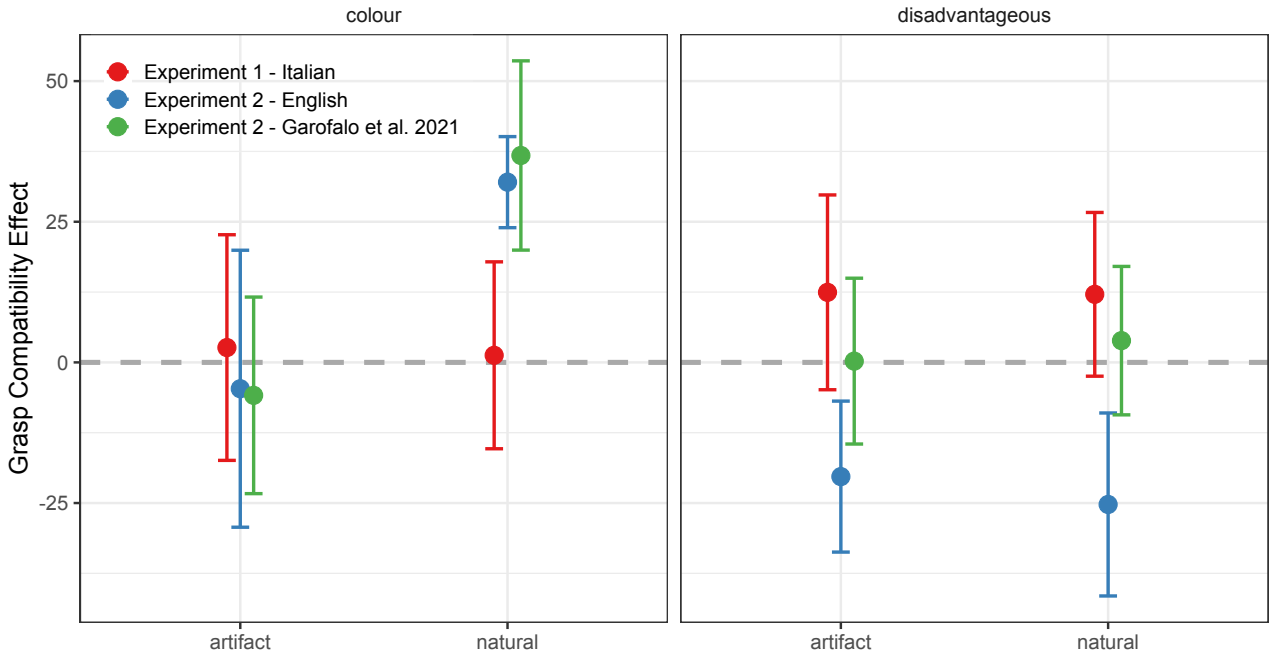

Figure 6. Averages values of grasp compatibility effects for Experiments 1 and 2 are shown in red and blue colours. We also added the averages values of grasp compatibility effects (green dots) taken from Garofalo et al. study (2021) for comparison. All averages are shown as a function of the Adjectives and Object Category factors. Error bars represent the 95% CIs calculated with the Cosineau-Morey method (Morey, 2008).

4. General Discussion

Recent evidence has suggested that adjectives modulate the grasp compatibility effect elicited by the categorization of object nouns. Here we report two experiments investigating whether this modulatory effect of adjectives is syntax-dependent. Crucially, the adjective was always presented in pre-nominal position and this adjective-noun order followed or not the syntactic rule of the language tested (English, Experiment 2 and Italian, Experiment 1, respectively). A reach-to-grasp compatibility task was used in both experiments. Results revealed no significant grasp compatibility effect when the adjective-noun syntactic order was violated (Experiment 1, Italian language). By contrast, when the adjective-noun order was syntactically correct (Experiment 2, English language), strong modulations of the grasp compatibility effect by the adjectives emerged. Even though the order of presentation of nouns and adjectives was the same in both Experiments, different results emerged depending on whether the syntactic rule was met or not (see Figure 6, for comparison). We interpreted these findings as evidence that adjectives are integrated in the sensorimotor representation of the noun categories. These findings are clearly in favour of an interplay between semantic and syntactic aspects of language that shapes the sensorimotor processes activated during the processing of adjective-noun combinations.

4.1. Noun-adjective combinations following syntactic rules.

An important finding of this study is that results of Experiment 2 replicated previous observations obtained with the combination of nouns and adjectives in Italian (Garofalo et al., 2021, see Figure 6). Although the position of the adjective is usually post-nominal in Italian and pre-nominal in English, overall comparable results were found in both languages and across different experiments. Thus, when the syntax was not violated, the modulatory impact of the adjective over the noun was elicited even when the adjective was presented before the object noun.

This suggests that the effect of the adjective on the activation of the motor program elicited by the noun was not entirely dependent on the adjective position (before or after the noun), provided that syntax was not violated. In line with this observation, a recent work by Papitto and colleagues (2021), investigating the understanding of negation in the Italian and German languages, revealed little differences between languages in the sensorimotor inhibition driven by the position of the negation particles. These particles are usually in pre-verbal position in Italian and in post-verbal position (at the end of the sentence) in German. The lack of difference between languages suggested that the involvement of the sensorimotor system engaged by the negation process was unaffected by the position of the particle when the syntax was not violated. This latter aspect of Papitto and colleagues' study appears to support our observation that the modulatory effect of the adjective on the object noun was observed both when the adjective was in pre-nominal position (Experiment 2, English language) and when it was in post-nominal position (Garofalo et al., 2021, Italian language).

However, the impact of the disadvantageous adjective on both categories of objects observed in the English language (Experiment 2) appeared to be particularly strong, resulting in an inverted grasp compatibility effect. In Italian, when the adjective was presented in post-nominal position the grasp-compatibility effect disappears but does not reverse (Garofalo et al., 2021). This implies that, when the disadvantageous adjective was presented first, the motor program driven by the noun was not only blocked, but also inhibited. Thus, the order of presentation of the words in the combination is likely to play a role into the sensorimotor integration between the meaning of the noun and the adjective. The idea of a modulatory role of word position on sensorimotor activation has been suggested recently by a study on adverbs and verbs in the German language (Sieksmeyer et al. 2021). In two experiments, the authors presented foot and hand action verbs combined with adverbs defining the manner in which the action should be performed (e.g., forcefully vs. feebly). Adverbs were presented in pre-verbal position or in post-verbal position in Experiment 1 and 2, respectively. This study showed that if the manner adverbs were placed in pre-verbal position, the effect was more pronounced compared to when the adverbs followed the verbs. Furthermore, it is important to note that in German the position of the manner adverb is not fixed, but generally the adverb comes close to the verb it refers to, so both verb-adverb or adverb-verb orders were syntactically correct. Thus, when two words are presented at the same time, there seems to be a 'primacy effect' such that the meaning of the first word has a stronger modulatory impact on the following word compared to the opposite presentation order (provided that syntax is not violated).

4.2. Noun-adjective combinations violating syntactic rules

In Experiment 1, in which the Italian syntactic rule of adjective placement was breached, results revealed no main effect of grasp compatibility nor its interaction with different adjectives or nouns categories, demonstrating that the reach-to-grasp compatibility effect was not reliably present in this experiment. The absence of any grasp compatibility effects is clearly in contrast with results observed in Experiment 2 of the present study, but also with Garofalo et al. (2021, Experiments 2 and 3), in which the syntactic rule of the language was met. Together these observations clearly support the hypothesis that syntax plays a fundamental role in the sensorimotor processes even when it is completely irrelevant to the task.

Numerous evidence from psychophysiological studies have shown that syntax is automatically processed and its violations are automatically detected (e.g., Coulson et al., 1998; Friederici et al., 1996a; Hasting et al., 2007). For example, specific ERP components seem to be selectively sensitive to syntactic processing. Violations of the word category, that is the mismatch between actual and the required word category, affected the early left anterior negativity (ELAN), that occurs 150 ms

after the onset of the violation (e.g., Friederici et al., 1996b; Hasting et al., 2007; Neville et al., 1991). Violations that affect the tense, number or gender agreement are able to modulate the later anterior negativity (LAN), that occurs between 300 and 500 ms after the onset of the error (e.g., Coulson et al., 1998; Osterhout & Mobley, 1995). Finally, the P600 component (SPS - Syntactic positive shift, Osterhout & Holcomb, 1993) is also sensitive to syntactic violations involving positional aspects of word categories in the phrase structure (e.g., Friederici et al., 1996b; Hagoort, 2003).

These electrophysiological results are in line with the argument of an interplay between syntax and semantics during language comprehension proposed by Pulvermüller and colleagues (1999, 2010, 2013). The authors speculated that the combinatorial rules that define the syntax of a language can be computed by patterns of activation in functionally discrete neuronal assemblies and that this mechanism can account for the implementation of syntax in the brain following Hebbian rules. In other words, the authors proposed that syntax is encoded in the synchronized/a-synchronized firing chains of neurons, which work with sequence detectors establishing recursive connections with each other. Through the experience of grammatical and syntactical regularities, these recursive connections consolidate and form brain networks in which the interplay between semantics and syntax is embedded (Pulvermüller, 1999). These brain networks have been suggested to overlap with distinct action-perception circuits for hand, mouth and articulatory actions, which include temporo-parietal and pre-motor areas (Fadiga et al., 2009; Pulvermüller & Fadiga, 2010). Therefore, the combinatorial rules of syntactic structures may have an equivalent in the action domains reflecting a more general mechanism underlying physical interactions with the object (Pulvermüller & Fadiga, 2010). Syntax violations may lead to an unusual activation pattern of sequence detectors. By contrast, when the syntactic rules are met, as in Experiment 2, the neuronal detectors in the temporo-parietal-frontal circuits are activated leading to the modulation of the sensorimotor activation we found.

4.3. Noun local effect

As discussed in the previous section, the integrative processes between adjectives and nouns were disrupted when the usual syntactic order was violated. Importantly, however, this is not the only sensorimotor process involved in the understanding of language. In addition to the integrative processes between the various constituents necessary to understand the sentence in its entirety (global processes), also processes elicited by each constituent are activated upon words presentation (local processes). The presence of these two levels of processes has been suggested, for example by Marino and colleagues (2012) in a study comparing sensible and non-sensible sentences. While in sensible sentences, integrative simulations are active depending on the sensorimotor specificity of the single words, in non-sensible sentences the sensorimotor processes indicate a mutual independence among simulations evoked by the single elements of the sentence. In general terms, it seems that both local effects and the global effects are related to the interplay between syntactic and semantic processes.

Our results revealed a residual grasp compatibility effect driven by the noun but not modulated by the adjective also when the syntactic rule was violated (Experiment 1). This residual effect, evident mainly in the MTs, may be due to the local processes related to the semantic processing of the single word (i.e., the noun). It should be noted that when nouns are presented in isolation (Experiment 1, Garofalo et al. 2021) a similar trend was observed with a residual grasp compatibility effect in the MTs. Because the noun is the second word of the adjective-noun combination in the Experiments 1 and 2 of the present study, it is processed later (i.e., after the adjective), and its sensorimotor representation may still be active during the execution of the

response. It is therefore possible that the ordinal position of the single words impacts the time-course of the sensorimotor activation and that the word that is read second affects later motoric stages such as the execution of the movement.

5. Conclusion

To sum up, our study provides one of the first evidence for a role of syntax in the sensorimotor processes elicited by language understanding. To the best of our knowledge, there are very few experimental studies addressing this issue (Koranda et al., 2020; Lebkuecher et al., 2022; Roy et al., 2013), and no one investigating it by means of combinations of nouns and adjectives. Our results showed that when the syntax is violated no modulatory effect of the adjectives emerges and no grasp compatibility effect is observed. When the syntax is correct, the modulatory effect of the adjective previously found in Italian is replicated in English, even if the position of the adjective is reversed as compared to Italian. These findings are in line with theories of embodied cognition which state that the understanding of language re-recruits the same neuronal sensory, motor, and emotional systems involved in experiencing the content of words. Hence, the linguistic experience (i.e., the learned rules and the regularities of grammatic and syntax) plays a role in the sensorimotor processes involved in the understanding of the coupling between two or more words which allows to build up a sentence. Furthermore, a positional effect of single words is found in both experiments, demonstrating a certain variation of motor involvement in language processing (Sieksmeyer et al., 2021), according to the syntactic rules of the language considered. When the adjectives are placed in pre-nominal position, they seem to influence the sensorimotor activation driven by nouns more strongly than the adjectives placed in post-nominal one, but only when the combination follows the correct syntax rule. Therefore, sensorimotor simulation seems to be susceptible to the syntactic constructions that modulate the characteristics of the motor programs elicited by the noun. In conclusion, results of the present study clearly demonstrate the importance of cross-language differences which should be considered when investigating the relationship between language and action.

Acknowledgments
We thank Alberto Arfini for his help in collecting the data of Experiment 1 and Brooke Benz for her help in adapting the stimuli for Experiment 2.

Funding
This work was partially supported by University of Bologna (AlmaIdea grant).

Competing interests
The authors have declared that no competing interests exist.

Author contributions
GG: Conceptualization, Data curation; Formal Analysis; Investigation; Software; Visualization; Writing – original draft; EG: Project administration; Supervision; Writing – original draft; Writing – review and editing; LR: Conceptualization; Methodology; Writing - original draft; Writing - review & editing.

Open Practices Statement
The datasets generated during the current study are shared via figshare repository: https://figshare.com/account/articles/23744025**.** None of the experiments was preregistered.

References

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

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

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

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

Bompas, A., Kendall, G., & Sumner, P. (2013). Spotting fruit versus picking fruit as the selective advantage of human colour vision. *I-Perception*, *4*(2), 84–94. https://doi.org/10.1068/i0564

Borghi, A. M., & Cangelosi, A. (2014). Action and language integration: From humans to cognitive robots. *Topics in Cognitive Science*, *6*(3), 344–358. https://doi.org/10.1111/tops.12103

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

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.

Britt, A. E., Ferrara, C., & Mirman, D. (2016). Distinct effects of lexical and semantic competition during picture naming in younger adults, older adults, and people with aphasia. *Frontiers in Psychology*, *7*(JUN), 1–17. https://doi.org/10.3389/fpsyg.2016.00813

Bub, D. N., & Masson, M. E. J. (2010). On the nature of hand-action representations evoked during written sentence comprehension. *Cognition*, *116*(3), 394–408. https://doi.org/10.1016/j.cognition.2010.06.001

Bub, D. N., & Masson, M. E. J. (2012). On the dynamics of action representations evoked by names of manipulable objects. *Journal of Experimental Psychology: General*, *141*(3), 502–517. https://doi.org/10.1037/a0026748

Buccino, G., Colagè, I., Gobbi, N., & Bonaccorso, G. (2016). Grounding meaning in experience: A broad perspective on embodied language. *Neuroscience and Biobehavioral Reviews*, *69*, 69–78. https://doi.org/10.1016/j.neubiorev.2016.07.033

Buccino, G., Sato, M., Cattaneo, L., Rodà, F., & Riggio, L. (2009). Broken affordances, broken objects: A TMS study. *Neuropsychologia*, *47*(14), 3074–3078. https://doi.org/10.1016/j.neuropsychologia.2009.07.003

Castiello, U. (1996). Grasping a Fruit: Selection for Action. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(3), 582–603. https://doi.org/10.1037/0096-1523.22.3.582

Castiello, U. (1999). Mechanisms of selection for the control of hand action. In *Trends in Cognitive Sciences* (Vol. 3, Issue 7, pp. 264–271). https://doi.org/10.1016/S1364-6613(99)01346-7

Castiello, U. (2005). The neuroscience of grasping. *Nature Reviews Neuroscience*, *6*(9), 726–736. https://doi.org/10.1038/nrn1744

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.

Coulson, S., King, J. W., & Kutas, M. (1998). Expect the unexpected: Event-related brain potentials to morphosyntactic violations. *Language and Cognitive Processes*, *13*(1), 21–58.
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
Cumming, G. (2014). The New Statistics: Why and How. *Psychological Science*, *25*(1), 7–29. https://doi.org/10.1177/0956797613504966
Del Maschio, N., Fedeli, D., Garofalo, G., & Buccino, G. (2022). Evidence for the Concreteness of Abstract Language: A Meta-Analysis of Neuroimaging Studies. *Brain Sciences*, *12*(1), 1–21. https://doi.org/10.3390/brainsci12010032
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
Fadiga, L., Craighero, L., & D'Ausilio, A. (2009). Broca's area in language, action, and music. *Annals of the New York Academy of Sciences*, *1169*, 448–458. https://doi.org/10.1111/j.1749-6632.2009.04582.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
Friederici, A. D., Hahne, A., & Mecklinger, A. (1996a). Temporal structure of syntactic parsing: Early and late event-related brain potential effects. *Journal of Experimental Psychology: Learning Memory and Cognition*, *22*(5), 1219–1248. https://doi.org/10.1037/0278-7393.22.5.1219
Friederici, A. D., Hahne, A., & Mecklinger, A. (1996b). Temporal structure of syntactic parsing: Early and late event-related brain potential effects. *Journal of Experimental Psychology: Learning Memory and Cognition*, *22*(5), 1219–1248. https://doi.org/10.1037/0278-7393.22.5.1219
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., & 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
Garofalo, G., Magliocco, F., Silipo, F., Riggio, L., & Buccino, G. (2022). What matters is the underlying experience: Similar motor responses during processing observed hand actions and hand-related verbs. *Journal of Neuropsychology*, *16*(2), 389–406. https://doi.org/10.1111/jnp.12270
Garofalo, G., Marino, B. F. M., Bellelli, S., & Riggio, L. (2021). Adjectives Modulate Sensorimotor Activation Driven by Nouns. *Cognitive Science*, *45*(3), 1–36. https://doi.org/10.1111/cogs.12953
Garofalo, G., & Riggio, L. (2022). Influence of colour on object motor representation. *Neuropsychologia*, *164*(October 2021), 108103. https://doi.org/10.1016/j.neuropsychologia.2021.108103
Gentilucci, M., Benuzzi, F., Bertolani, L., Daprati, E., & Gangitano, M. (2000). Language and motor control. *Experimental Brain Research*, *133*(4), 468–490. https://doi.org/10.1007/s002210000431
Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, *27*(01), 3–78. https://doi.org/10.1017/s0140525x04280025
Glover, S., & Dixon, P. (2002). Semantics affect the planning but not control of grasping. *Experimental Brain Research*, *146*(3), 383–387. https://doi.org/10.1007/s00221-002-1222-6

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

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

Green, P., & Macleod, C. J. (2016). SIMR: An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution*, *7*(4), 493–498. https://doi.org/10.1111/2041-210X.12504

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

Hagoort, P. (2003). Interplay between syntax and semantics during sentence comprehension: ERP effects of combining syntactic and semantic violations. *Journal of Cognitive Neuroscience*, *15*(6), 883–899. https://doi.org/10.1162/089892903322370807

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

Hasting, A. S., Kotz, S. A., & Friederici, A. D. (2007). Setting the stage for automatic syntax processing: The mismatch negativity as an indicator of syntactic priming. *Journal of Cognitive Neuroscience*, *19*(3), 386–400. https://doi.org/10.1162/jocn.2007.19.3.386

Jax, S. A., & Buxbaum, L. J. (2010). Response interference between functional and structural actions linked to the same familiar object. *Cognition*, *115*(2), 350–355. https://doi.org/10.1016/j.cognition.2010.01.004

Jeannerod, M. (1984). The Timing of Natural Prehension Movements. *Journal of Motor Behavior*, *16*(3), 235–254. https://doi.org/10.1080/00222895.1984.10735319

Kemmerer, D. (2022). Revisiting the relation between syntax, action, and left BA44. *Frontiers in Human Neuroscience*, *16*(September), 1–14. https://doi.org/10.3389/fnhum.2022.923022

Klein Entink, R. H., Kuhn, J.-T., Hornke, L. F., & Fox, J.-P. (2009). Evaluating cognitive theory: A joint modeling approach using responses and response times. *Psychological Methods*, *14*(1), 54–75. https://doi.org/10.1037/a0014877

Klepp, A., Niccolai, V., Sieksmeyer, J., Arnzen, S., Indefrey, P., Schnitzler, A., & Biermann-Ruben, K. (2017). Body-part specific interactions of action verb processing with motor behaviour. *Behavioural Brain Research*, *328*(December 2016), 149–158. https://doi.org/10.1016/j.bbr.2017.04.002

Kline, R. B. (2004). *Beyond significance testing: Reforming data analysis methods in behavioral research.* (A. P. Association, Ed.). https://doi.org/doi:10.1037/10693-000

Koranda, M. J., Bulgarelli, F., Weiss, D. J., & MacDonald, M. C. (2020). Is Language Production Planning Emergent From Action Planning? A Preliminary Investigation. *Frontiers in Psychology*, *11*(June), 1–11. https://doi.org/10.3389/fpsyg.2020.01193

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

Lebkuecher, A. L., Schwob, N., Kabasa, M., Gussow, A. E., MacDonald, M. C., & Weiss, D. J. (2022). Hysteresis in motor and language production. *Quarterly Journal of Experimental Psychology*. https://doi.org/10.1177/17470218221094568

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

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

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

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*, *23*(4), 979–990. https://doi.org/10.3758/s13423-015-0842-3

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

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, *94*, 305–315. https://doi.org/10.1016/j.jml.2017.01.001

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

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

Neville, H., Nicol, J. L., Barss, A., Forster, K. I., & Garrett, M. F. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, *3*(2), 151–165. https://doi.org/10.1162/jocn.1991.3.2.151

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

Osterhout, L., & Holcomb, P. J. (1993). Event-Related Brain Potentials Elicited by Syntactic Anomaly. *Journal of Memory and Language*, *8*(4), 439–483.

Osterhout, L., & Mobley, L. A. (1995). Event-Related Brain Potentials Elicited by Failure to Agree. In *Journal of Memory and Language* (Vol. 34, Issue 6, pp. 739–773). https://doi.org/10.1006/jmla.1995.1033

Papitto, G., Lugli, L., Borghi, A. M., Pellicano, A., & Binkofski, F. (2021). Embodied negation and levels of concreteness: A TMS study on German and Italian language processing. *Brain Research*, *1767*(April), 147523. https://doi.org/10.1016/j.brainres.2021.147523

Pulvermüller, F. (1999). Words in brain s language. *Behavioral and Brain Science*, *22*(1999), 253–336.

Pulvermüller, F. (2010). Brain embodiment of syntax and grammar: Discrete combinatorial mechanisms spelt out in neuronal circuits. *Brain and Language*, *112*(3), 167–179. https://doi.org/10.1016/j.bandl.2009.08.002

Pulvermüller, F. (2013). How neurons make meaning: Brain mechanisms for embodied and abstract-symbolic semantics. *Trends in Cognitive Sciences*, *17*(9), 458–470. https://doi.org/10.1016/j.tics.2013.06.004

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

R Core Team. (2020). *R: A language and environment for statistical computing* (3.6.3). R Foundation for Statistical Computing.

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., Patteri, I., Oppo, A., & Buccino, G. (2006). The role of affordances in inhibition of return. *Psychonomic Bulletin & Review*, *13*(6), 1085–1090.

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

Roy, A. C., & Arbib, M. A. (2005). The syntactic motor system. *Gesture*, *5*(1–2), 7–37. https://doi.org/https://doi.org/10.1075/gest.5.1.03roy

Roy, A. C., Curie, A., Nazir, T., Paulignan, Y., des Portes, V., Fourneret, P., & Deprez, V. (2013). Syntax at Hand: Common Syntactic Structures for Actions and Language. *PLoS ONE*, *8*(8), 1–11. https://doi.org/10.1371/journal.pone.0072677

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

Sakreida, K., Effnert, I., Thill, S., Menz, M. M., Jirak, D., Eickhoff, C. R., Ziemke, T., Eickhoff, S. B., Borghi, A. M., & 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

Sassenhagen, J., & Alday, P. M. (2016). A common misapplication of statistical inference: Nuisance control with null-hypothesis significance tests. *Brain and Language*, *162*, 42–45. https://doi.org/10.1016/j.bandl.2016.08.001

Serianni, L. (1989). *Grammatica Italiana: suoni, forme, costrutti*. Utet, Torino.

Sieksmeyer, J., Klepp, A., Niccolai, V., Metzlaff, J., Schnitzler, A., & Biermann-ruben, K. (n.d.). *Influence of Manner Adverbs on Action Verb Processing*. Springer International Publishing. https://doi.org/10.1007/978-3-030-50200-3

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

Symes, E., Tucker, M., Ellis, R., Vainio, L., & Ottoboni, G. (2008). Grasp preparation improves change detection for congruent objects. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(4), 854–871. https://doi.org/10.1037/0096-1523.34.4.854

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

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

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., 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

Vigliocco, G., Meteyard, L., Andrews, M., & Kousta, S. (2009). Toward a theory of semantic representation. *Language and Cognition*, *1*(2), 219–247. https://doi.org/10.1515/langcog.2009.011

Visani, E., Magliocco, F., Sebastiano, D. R., Duran, D., Garofalo, G., Magliocco, F., Silipo, F., & Buccino, G. (2021). The Semantics of Natural Objects and Tools in the Brain : A Combined Behavioural and MEG Study. *Brain Sciences*, *12*(1), 1–22. https://doi.org/10.3390/brainsci12010097

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