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## Inhibitory mechanisms are affected by stimulus-response congruency<sup>☆</sup>

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### ABSTRACT

Embodied cognition theories propose that higher-order cognitive functions are grounded in the activity of cerebral systems supporting lower-level sensorimotor interactions between the body and the environment. However, the way in which sensorimotor body representations affect higher cognitive functions, such as cognitive control, is still not defined. Here we investigate in two Experiments whether the bodily content of visual stimuli and their stimulus-response congruency modulate motor inhibition, i.e., a key function of cognitive control. Participants completed an online manual Go/No-Go task on visual stimuli belonging to three categories (bodily-related: a right hand, and non-bodily related: a shape and a leaf) (Exp 1). Results show slower reaction times and lower accuracy in Go trials for hand compared to non-body images. We further investigated how the degree of stimulus-response congruency (left-hand vs right-hand stimuli) modulates the inhibitory resources (Exp 2). The data from the two experiments were compared to test whether the category (i.e., body vs. non-body images; Exp 1) or sensorimotor representations (i.e., hand stimulus-response congruency; Exp 2) affect inhibitory mechanisms differently. Results show stronger interference with high levels of congruency and support that bodily content influences response inhibition performance in accordance with an embodied view of cognitive functions.

### Public significance statement

This study tested the possibility that cognitive control, a process that allows adaptive behaviour towards different goals and situations, is affected by the degree of stimulus-response compatibility. The results support a flexible interpretation of cognitive control processes which can be modulated by the content of the visual stimuli and their congruency with behavioural responses, rather than behaving as a mechanism fully independent from sensorimotor contingencies such as stimulus-response compatibility.

### Introduction

Embodied cognition theories propose that higher-order cognitive functions are grounded in the activity of cerebral systems supporting lower-level sensorimotor interactions between the body and the environment (Barsalou, 2008, 2010). Experimental studies have shown the engagement of visual, somatosensory and motor networks associated with the representation of the observer's body, during visual body perception (Bracci et al., 2010; Candidi et al., 2008; Downing and Kanwisher, 2001; Moreau et al., 2018, 2020; Moro et al., 2012; Orlov et al.,

2010; Peelen and Downing, 2007; Urgesi et al., 2006, 2007), visual memory for bodies (Galvez-Pol et al., 2018; Galvez-Pol et al., 2018), visual attention to body images (Arslanova et al., 2019; Joly-Mascheroni et al., 2021; Sel et al., 2014), conscious perception of emotional body movements and postures (Candidi et al., 2011, 2015) and visual emotion recognition in faces (Pitcher et al., 2009; Sel et al., 2014), amongst other processes. In addition, premotor and motor regions are engaged during basic body movement or action perception (Calvo-merino et al., 2006; Calvo-Merino et al., 2005; Cross et al., 2006) as well as during processing of abstract action representations, such as processing action-related verbs (Buccino et al., 2005; Candidi et al., 2010a; Candidi et al., 2010b; Glenberg et al., 2008; Hauk et al., 2004; Meister et al., 2003; Tettamanti et al., 2005). Studies on mental rotation show that the mental manipulation of images activates motor areas only when acting on hands, not objects (de Lange et al., 2006; Tomasino et al., 2005). The ability to mentally rotate body-related stimuli is affected by one's actual posture (Ionta and Blanke, 2009) and handedness as shown by studies reporting faster reaction times for right-handed than left-handed individuals and response facilitation for congruent images, as right-hand images in right-handers (Conson et al., 2013; Jones et al., 2021; Takeda et al., 2010; Zapala et al., 2021). Interferential brain

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stimulation (Avenanti et al., 2013; Candidi et al., 2008; Curtin et al., 2019; D'Ausilio et al., 2009; Fusco et al., 2020; Labruna et al., 2019; Pitcher et al., 2008; Pourtois et al., 2004; Urgesi et al., 2006) and lesion studies (Keysers et al., 2018; Moro et al., 2022; Moro et al., 2008; Urgesi et al., 2014) have supported the idea that perceiving body images automatically activates multisensory representations of one's own body in distributed cortical networks, and that many perceptual, affective and cognitive functions depend on these activations.

Given the role of sensorimotor and motor processes for perception, it is entirely possible that, conversely, the content of perceived stimuli affects the elaboration of motor responses through two mechanisms. First, a categorical effect by which the bodily content of a stimulus evokes body- and/or action-related representations which interact with the motor response representations (Buccino et al., 2005; Galvez-Pol et al., 2020a, 2020b). Second, stimulus-response compatibility effects by which the compatibility between the perceived stimulus and the motor response affects motor performance (Barsalou, 1999; Brass et al., 2000; Hommel, 2015a; Romano et al., 2019). Both bodily content and degrees of perceptual/response compatibility influence the interaction between perception and motor responses affecting the ability to control one's behaviour.

A critical function that allows humans to behave efficiently is called cognitive control. Cognitive control is the ability to adapt behaviour by planning, monitoring, and inhibiting inappropriate responses to achieve a specific goal (Chiu and Egner, 2019; Egner et al., 2010; Gavazzi et al., 2020). Typical cognitive control tasks require coping with changing contextual demands and switching between goals. We thus decided to use the Go/No-Go task to test the relation between perceptual, motor and inhibitory processes because it efficiently measures motor inhibition and is widely used to study cognitive control (Benedetti et al., 2020; Gomez et al., 2007). The Go/No-go task requires participants to respond as soon as possible to the Go stimulus while not responding to the No-go stimulus. The frequency of Go and No-go stimuli is manipulated to create a tendency to respond (Aron, 2014; Cooper et al., 2016) and the conflict created by the less frequent No-go stimulus requires increased control to inhibit the motor response (Wessel, 2018). In cognitive control tasks, Congruency sequence effects (CSE) are an index of adaptation, showing increased control after an effortful trial, resulting in better performance (Egner, 2007; Weissman et al., 2014).

While researchers traditionally considered cognitive control as independently supervising other cognitive processes in a top-down only fashion (Botvinick et al., 2001; Diamond, 2013), embodied theories inspire an alternative interpretation of cognitive control. Specifically, since cognitive control allows flexible response adaptation, it could be grounded in, or sensitive to, lower-level sensorimotor processes involved in body and action representations (Braem and Egner, 2018; Fusco et al., 2020). Studies on motor inhibition in silent reading have shown that negation recruits inhibitory networks, thus suggesting that sensorimotor body/action representations may influence inhibitory mechanisms (Liuzza et al., 2011; Montalti et al., 2021; Vitale et al., 2022). Following this alternative view, whether motor inhibition is affected by categorical and/or specific sensorimotor body representations is unknown. Here we aim to explore the proposal of an embodied nature of cognitive control.

In a series of studies, we investigated whether the bodily (hand) or non-bodily (shape and leaf) content of visual stimuli affects motor inhibition using a Go/No-Go task. In two experiments, we presented left- and right-hand images respectively. Hand images evoke both categorical and sensorimotor representations of the body, but the representations evoked by right-hand images (Experiment 2), compared to left hands images (Experiment 1), share a higher degree of stimulus-response congruency. These different levels of congruency of evoked sensorimotor representations allow us to investigate the effects of the activation of the category body and the specific representation of the hand used to respond, i.e., the two hypotheses referred to as categorical and sensorimotor. In Experiment 1, we tested a general categorical hypothesis, i.e., that visually perceiving a body part modulates inhibitory

performance. In Experiment 2, we tested the more stringent "sensorimotor-congruency" hypothesis – that perceiving an image of the same hand used to respond brings about a more substantial modulatory effect of inhibitory mechanisms. We measured congruency sequence effects to evaluate whether the body content of the stimulus also affects cognitive adaptation of motor responses. We hypothesize an impaired adaptive performance for body stimuli compared to non-body stimuli as the perception of body-related stimuli evoke categorical (Exp 1) and specific sensorimotor body representations (Exp 2).

Following the evidence about the compatibility between stimulus and motor response (Brass et al., 2000; Hommel et al., 2001) we tested an additional exploratory hypothesis. In both experiments, two different hand Go images were used, with one image showing a bent index finger and the other showing a straight index finger, while the right index finger was always used to respond. We hypothesize that the different degrees of compatibility between the observed hand (right and left) and the effector (right hand) may affect the response differently at the level of the posture of the index finger used to respond. Here we index the way inhibitory mechanisms may be influenced by these automatic body and motor representation activation by contrasting the bodily content of the hand stimuli with non-bodily stimuli that share the overall outline and size (Galvez-Pol et al., 2018) and are similarly natural, well-known, and with a similar proximal/distal organization of components (Moreau et al., 2018, 2020; Taylor et al., 2007,2010).

### *Experiment 1 – categorical congruency hypothesis*

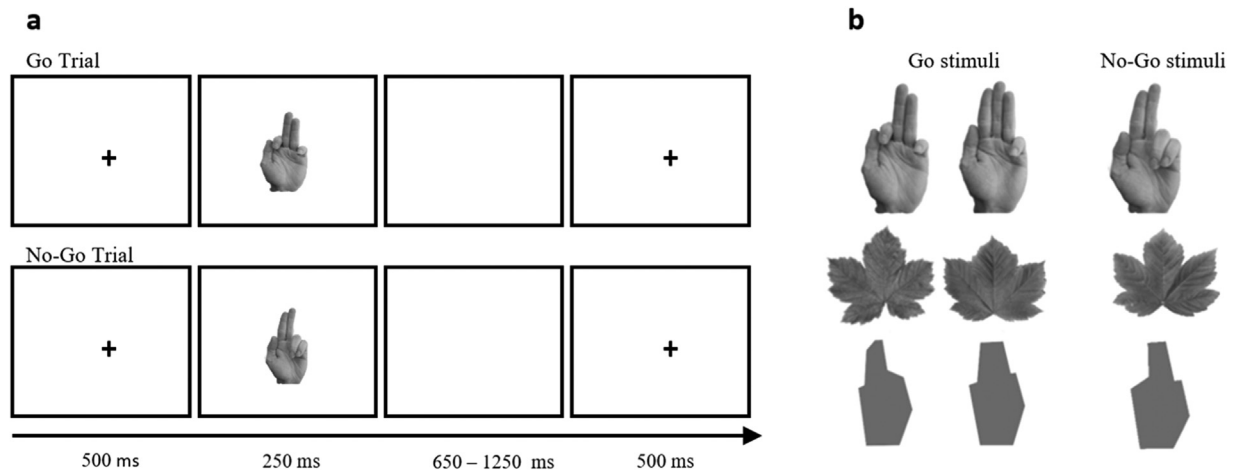
## Methods

### *Participants*

Before collecting data, we conducted a priori power analyses in MorePower (Campbell and Thompson, 2012) for a  $3 \times 2$  design assuming an alpha 2-sides criterion of 0.05 and a power = 0.80, which revealed, with a sample size of 40 participants, that the effect size that could be detected was  $\eta_p^2 = 0.11$  for the Stimuli x Sequence interaction, in line with the literature on motor inhibition using the Go/ No-Go task (Gavazzi et al., 2020). A total of 40 (40 females, age  $M = 19.50$ ,  $SD = 3.13$ ) university students voluntarily participated in the experiment for university credits. Given that we had no exclusion criteria for gender or age, we accepted any participant in order of application until reaching the planned sample size without balancing gender. All participants were right-handed. Participants were recruited through the Sona system of the university and participated via the online platform Testable (<https://www.testable.org/>). Participants could only use computers (Windows or Mac Os) thanks to Testable in-built features. Participants were able to read and accept the consent form online. Only once they have accepted the consent form could they proceed with the study. The study was performed according to the Declaration of Helsinki and was approved by the Research Committee of City, University of London (ETH2021–1106). All participants had normal or corrected-to-normal vision and were blind to the purpose of the study before the experimental session.

### *Stimuli*

To test the hypothesis of the role of body representations on inhibitory mechanisms, we compared images of three categories, namely hand for the body condition and shape and leaf images for the non-body control conditions, as they were successfully implemented in similar relevant studies. In the hand condition, we presented left-hand images showing the palm with either the little finger, index and little finger, or ring with the little finger bent. We selected hand images with different positions of the index finger to investigate further the role of sensorimotor congruency (see comparison analysis after experiment 2). We used left-hand images because of their lower congruency with the right hand



**Fig. 1.** Example of the trial scheme and stimuli.

*Note.* (a) example of a Go trial and a No-Go trial. Inter-trial interval starts after the end of the target presentation for 650–1250 ms. Participants' response times are calculated from the beginning of the target presentation until the end of the inter-trial-interval. (b) Go and No-Go stimuli were used in the experiment. The top row represents hands, the middle row represents leaves, and the bottom row represents shapes.

used to respond compared to the stimuli used in Experiment 2. As control stimuli, we selected two categories of images. The shape category is composed of geometrical shapes created by matching the hands' outline and size (Galvez-Pol et al., 2018). For the leaf category, we presented palmately lobed leaves (Moreau et al., 2018). Each category of stimuli forms a separate condition, and all the three categories are treated independently in the analyses. All the images were grayscales and were matched for contrast and luminance using the Curves tool in Gimp software (The GIMP Development Team (2019) *GIMP*). For the hand category, the 2 Go stimuli showed the hand with the little, and index-little fingers bent, while the No-Go Stimuli was the image showing the hand with the ring-little fingers bent.

#### Experimental procedure

Participants performed a Go/No-Go task (75/25% ratio) in a within-subject design with the factor of Stimuli (hand, shape, leaf) and were instructed to use their right index finger to respond (Fig. 1b). Note that the Accuracy (ACC) analyses were based on No-Go trials since the task tests the ability to inhibit prepotent responses; conversely, Reaction Time (RT) analyses were based on Go trials only since No-Go trials do not have any RTs.

Each trial started with a fixation cross in the centre of the screen (500 ms), followed by a target image that lasted 250 ms and disappeared after that, followed by a blank screen that lasted for a variable inter-trial-interval (ITI) (between 650 and 1250 ms) before the next trial started, for a total time of trial ranging between 1400 and 2000 ms. Participants could respond from the beginning of the target presentation until the end of the variable inter-trial-interval, therefore responses could range up to a maximum of 1500 ms after stimulus appearance (250 ms of stimulus presentation plus 1250 ms of ITI). Participants were instructed to respond by pressing the spacebar using their right index finger as fast and as correctly as possible when they saw a Go Stimuli while withholding the response when they saw a No-Go Stimulus (see Fig. 1a).

The experiment had 3 blocks of trials, one for each type of stimuli. The presentation order of the blocks was randomized to avoid practice effects. Each block contained 3 sub-blocks of 64 trials each (48 Go, 16 No-Go) for a total number of 576 trials (144 No-Go). Participants were instructed to pause between sub-blocks for max 2 min. At the beginning of each block, there was a practice session of 12 trials (9 Go, 3 No-Go) and participants had to respond correctly in at least 9 trials to proceed to the experimental block. We collected the RTs and the Accuracy of the responses. The ratio between Go trials and No-Go trials was set to 3:1

and each type of Stimuli contained 2 Go and 1 No-Go image (Fig. 1b) to maximize errors (Young et al., 2018). The total time of the experiment was around 30 min.

One participant was removed as more than 40% of the trials showed a reaction time shorter than 200 ms following the assumption of the necessary encoding and execution time compared to fast guesses (Berger et al., 2021; Palmer et al., 2011; Whelan, 2008). Afterwards, we removed all trials that showed response times below 200 ms and performed Median Absolute Deviation (MAD) on outliers (Hedge et al., 2018; Leys et al., 2013; Ratcliff, 1993; Ratcliff et al., 2018): a total of 310 Go trials were removed (1.4% of the total, median = 94.5 ms, IQR = 107.25 ms, SD = 60.32 ms). A total of 39 participants entered the analyses. The analyses were conducted using Matlab, Jasp and R.

#### Statistical approach

To test any difference in the ability to discriminate between Go and No-Go images and individuals' response bias across the conditions, before assessing our hypothesis that the (bodily) content of the stimuli modulates the top-down control of the motor responses, we ran repeated measure ANOVAs (rm-ANOVA) of the  $D'$  and criterion ( $c$ ) from Signal Detection Theory (Green and Swets, 1966) using only the factor Stimuli after checking that the assumptions for these tests were met. We used the package "psycho" to calculate the  $d'$  ( $d' = z(\text{hits}) - z(\text{false alarms})$ ) and  $c$  ( $c = z(\text{hits}) + z(\text{false alarms})$ ) indexes (Makowski, 2018). The  $d'$  is a measure of task sensitivity and as the difficulty of the task increases, the  $d'$  decreases. The response bias  $c$  indexes the tendency to choose to respond or not: a reluctant participant would produce fewer hits but also fewer false alarms. Negative values of  $c$  indicate a tendency to respond, while positive values indicate a reluctance to respond.

For RTs of correct Go trials, we performed a generalized linear mixed effect model using R (R Core Team, 2012) and "glmer" function in lme4 (Bates et al., 2015) using an Inverse-Gaussian distribution and identity link function (Lo and Andrews, 2015) as reaction times are not normally distributed (Baayen and Milin, 2010; Palmer et al., 2011; Ratcliff, 1993). Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. We started by running the model with full random structure (with Stimuli and Sequence (i.e., for RTs: Go trials following No-Go trials (No-Go – Go), and Go trials following Go trials (Go – Go)) as fixed factors and individuals, Stimuli and Sequence as random factors) justified by design (Barr et al., 2013) and performed model reduction to find the best-fitting model defined as the one minimizing the BIC (Bates et al., 2015) (see Supplementary Material for

the final structure of the model). Model comparison was performed using the function “anova” of lme4 and p-values were obtained using the “Anova” function from “car” package that implements Kenward-Roger corrected tests, while estimated marginal means for simple effect were obtained using the package “emmeans” with Tukey correction (Fox and Weisberg, 2019; Singmann and Kellen, 2019; Yu et al., 2022).

Similarly to RTs, for Accuracy (Acc) on No-Go trials, we performed generalized linear mixed models using a binomial distribution and logit link function (Jaeger, 2008; Yu et al., 2022). This approach tested the hypothesis that the proportion of correct responses in No-Go trials of the control conditions (Leaf and Shape in our case) was higher/lower than the reference accuracy (Hand in our case). Model selection was performed as described above.

In order to test whether null results of the frequentist analyses supported the absence of Bayesian evidence (Dienes, 2014) and whether significant frequentist effects close to the significance level were supported by the more conservative Bayesian approach (Lindley, 1957; Makowski et al., 2019), we also used Bayesian methods. The comparison between frequentist and Bayesian approaches is useful and provides a better understanding of the robustness of the pattern of results. The full Bayesian analyses are described and reported in the Supplementary Material but any discrepancy between frequentist and Bayesian approaches (Wetzels et al., 2011) is discussed in the main text.

### Transparency and openness

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study, and we follow JARS (Kazak, 2018). All data, analysis code and research materials are available at [<https://osf.io/y7g5w/>].

## Results

### D-prime and criterion c

We ran an rm-ANOVA with a factor of Stimuli on the  $d'$  (d-prime) and response criterion  $c$ . The results showed that  $d'$  was not significantly different across Stimuli ( $F(2,76) = 0.143, p = .867, \eta_p^2 = 0.004$ ). The  $c$  was slightly negative for all conditions (hands =  $-0.96$ , shapes =  $-1.08$ , leaves =  $-1.03$ ), but importantly the differences between Stimuli were not significant ( $F(2,76) = 1.836, p = .167, \eta_p^2 = 0.046$ ). Thus, task difficulty and the subject's criteria were not different across Stimuli conditions indicating that the ability to discriminate the Go stimuli from the No-Go stimuli did not differ across conditions, nor did the individuals' bias to respond. The Bayes factor approach showed strong evidence for a difference between Stimuli conditions for the  $d'$  ( $BF = 10.870$ ) and anecdotal evidence for the criterion  $c$  ( $BF = 2.83$ ). The values of omissions and false rates can be found in the Supplementary materials.

### Reaction times of Go trials

We ran a generalized linear mixed model on Reaction Times of correct Go trials. As fixed effects, the best model included Stimuli (hand/shape/leaf) and Sequence (No-Go – Go/Go – Go) (without interaction). As random effects, the model included slopes for Stimuli and Sequence (without interaction) and intercepts for Participants (see Supplementary Material for the final model). Consistent with our hypothesis, the simple effect of Stimuli significantly predicted reaction times ( $\chi^2 = 37.609, df = 2, p = .001$ ), showing that reaction times were slower for hand images (Estimated Mean (EM) = 503, SE = 6.34) compared to shape (EM = 473, SE = 8.36; estimated difference  $B = 30.39, SE = 6.18, p = .001$ ) and to leaf images (EM = 475, SE = 8.36; estimated difference  $B = 28.37, SE = 6.45, p = .001$ ) (Fig. 2), whilst no significant difference for shape compared to leaf images (estimated difference  $B = -2.03, SE = 8.06, p = .966$ ) was found. A simple fixed effect of Sequence was also found to be significant ( $\chi^2 = 14.36, df = 1, p = .001$ ), indicating

that reaction times were faster for Go trials preceded by a Go trial (EM mean = 475, SE = 6.33) compared to Go trials preceded by a No-Go trial (EM = 492, SE = 7.63, estimated difference  $B = -16.4, SE = 4.58, p = .001$ ).

Overall, and consistently with the results of the Bayesian analysis (Supplementary Material), the pattern of results indicates that individuals are slower when responding to hand images compared to other non-body stimuli and to Go trials preceded by No-Go trials.

### Accuracy of responses of No-Go trials

We ran a generalized linear mixed model on the accuracy of No-Go trials. As fixed effects, the best model included Stimuli (hand/shape/leaf) and Sequence (i.e., No-Go trials preceded by a Go trial (Go – No-Go), and No-Go trials preceded by a No-Go trial (No-Go – No-Go) (without interaction). As random effects, the model included 1) slopes for Stimuli and intercepts for Participants, and 2) slopes for Sequence and intercepts for Participants (see Supplementary Material for model).

The simple effect of Stimuli turned out to be marginally significant ( $\chi^2 = 6.082, df = 2, p = 0.048$ ), showing that accuracy in No-Go trials was lower for hand images (EM = 1.01, SE = 0.167) compared to shape (EM = 1.29, SE = 0.169; estimated difference  $B = -0.275, SE = 0.113, p = .04$ ), but not compared to leaf images (EM = 1.20, SE = 0.189; estimated difference  $B = -0.18, SE = 0.129, p = .38$ ), while no significant difference between shape and leaf images (estimated difference  $B = 0.09, SE = 0.131, p = .76$ ) was found. The simple effect of Sequence was significant ( $\chi^2 = 28.55, df = 1, p = .001$ ), showing that accuracy was lower for No-Go trials preceded by a Go trial (EM = 0.90, SE = 0.153; 3968 sequences) compared to No-Go trials preceded by a No-Go trial (EM = 1.435, SE = 0.181, estimated difference  $B = -0.538, SE = 0.101, p = .001$ ; 1274 sequences) – a typical finding that suggests that the response in a previous trial also affects the following trial.

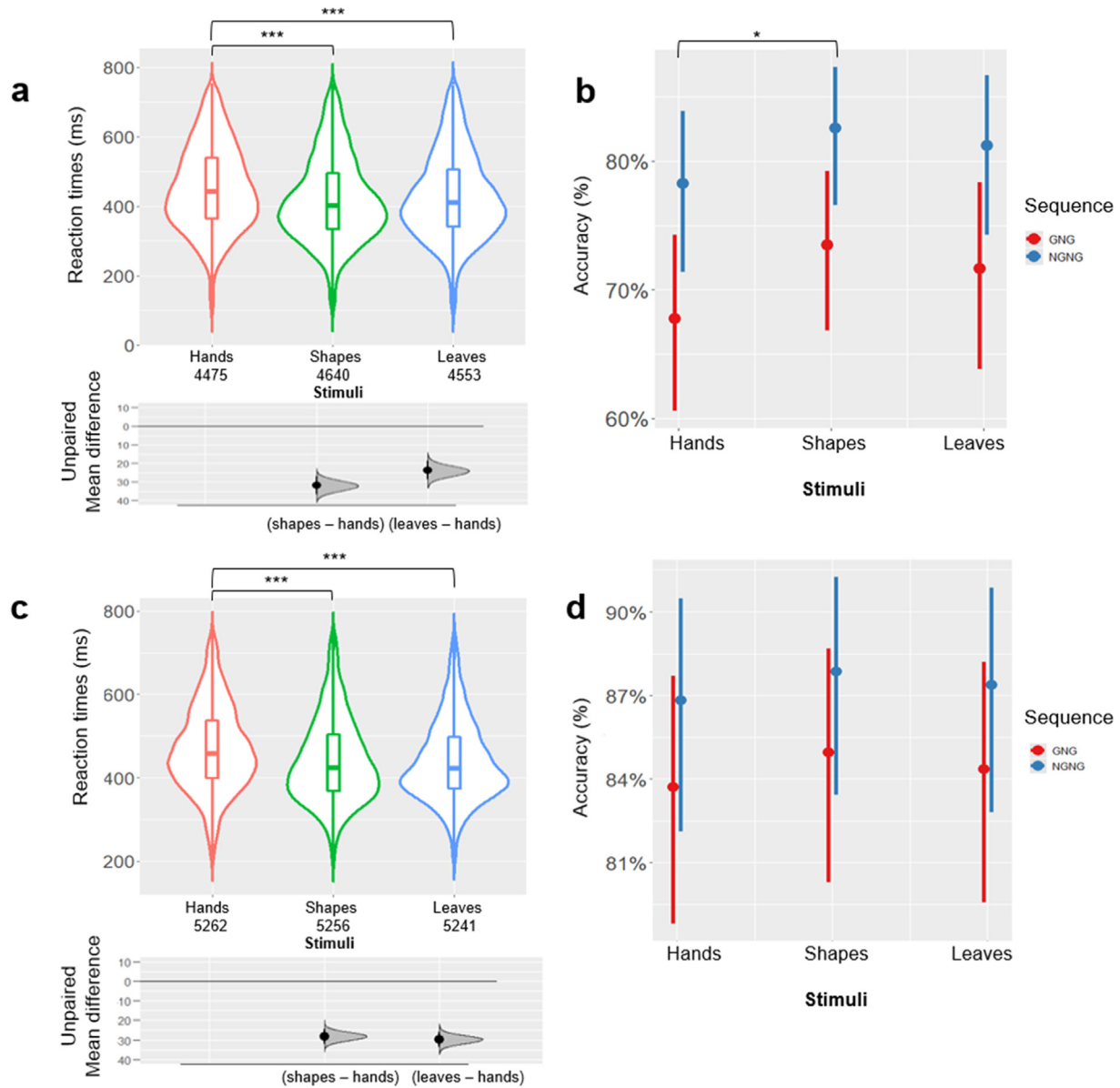
Overall, this pattern of results indicates that the ability to inhibit a hand response when dealing with hand images is slightly more demanding than other non-body conditions while the sequence of responses heavily affects response inhibition. The difference between the impact of the two factors is confirmed by the Bayesian analysis (Supplementary Material), which shows that the model that best predicts the data does not contain Stimuli but only the Sequence factor, which shows strong evidence. The reason why participants are less accurate at responding to stimuli to which they also respond slower may be attributed to the body feature of the stimuli and requires more research to unveil.

## Interim discussion

The results of Experiment 1 indicated that perceiving body-related images induced poorer performance (i.e., significantly longer RTs for Go trials and marginally significant lower Accuracy in No-Go trials) compared to non-body related stimuli and that the sequence of Go and No-Go trials heavily affected both RTs and Accuracy by specifically slowing RTs for hand stimuli and lowering Accuracy for both hand and control images. These results were supported by the analyses using a Bayesian approach which confirmed the same pattern for RTs and showed that the weak significance of the stimuli content in worsening the Accuracy of inhibition found with the frequentist approach was indeed paralleled by an absence of evidence that the stimulus content predicted the pattern of Accuracy (see Supplementary Material).

Since in Experiment 1 we used stimuli representing left hands while participants were asked to answer with their right hand, in Experiment 2 we used right-hand images to test whether the impairment of performance (longer RTs in Go trials) for hand images would be further modulated by the congruency between the laterality of the observed hand and the hand used to respond.

### Experiment 2 – sensorimotor-congruency hypothesis



**Fig. 2.** Reaction times and accuracy in the three Stimuli conditions (hand, shape, leaf) showing main effects of stimuli in experiment 1 and experiment 2.

*Note.* (a,b) Plots refer to experiment 1, (c,d) plots refer to experiment 2. (a, c) Figure showing the violin and estimation plots (<https://github.com/ACCLAB/dabestr> (Ho et al., 2019)) indicates significantly slower responses for hands compared to the other stimuli (leaves, shapes) in both experiments. Distributions of raw data are shown on top with summary measurements displayed as boxplot: the lines represent conventional mean (horizontal line) ± standard deviation error bars. (a, c) Below the violin plots, the graphs show the effect size as mean difference, with 95% CI and its resampled distribution as curve (value zero is the mean for the hand category). (b, d) The right plots show the significant effect of Stimuli and Sequence on Accuracy of No-Go trials as the difference in percentages between Stimuli and Sequence (b, experiment 1, d, experiment 2). The central dots represent the median ± standard deviation error bars. \*\*\* means  $p < .001$ .

**Methods**

*Participants*

In line with Experiment 1 and to maximize the similarity between the two experiments to test additional hypotheses (see section Experiment 1 vs 2), before collecting data we reproduced the same a priori power analysis in MorePower (Campbell and Thompson, 2012) for a  $3 \times 2$  design assuming an alpha 2-sides criterion of 0.05 and a power = 0.80 which revealed, with a sample size of 40 participants, that the effect size that could be detected was  $\eta_p^2 = 0.11$  for the Stimuli x Sequence interaction. This corresponds with the experiment reported above. A total of 40 (13 females, 27 males age  $M = 30$ ,  $SD = 10$ ) participants were randomly recruited through the online platform Testable Minds

(<https://minds.testable.org/>) and were paid £3 for their participation. We applied no exclusion criteria for gender or age. All participants but one were right-handed. Participants were able to read and accept the consent form online. Only once they have accepted the consent form they could proceed with the study. The study was performed according to the Declaration of Helsinki and was approved by the Research Committee of City, University of London (ETH2021–1106). All participants had normal or corrected-to-normal vision and were blind to the purpose of the study before the experimental session.

*Experimental procedures*

Stimuli were identical to those used in Experiment 1 except that the hand category showed right-hand images. Compared to the left-hand

images used in Experiment 1, we used right-hand images because of the higher congruency with the right hand used to respond. The design of the experiment was the same as Experiment 1. The data were pre-processed as in Experiment 1. We removed all trials that showed response times below 200 ms and performed Median Absolute Deviation (MAD) on outliers: a total of two trials were removed. All participants were included in the analyses.

### Statistical approaches

We used the same approach used in Experiment 1.

## Results

### D-prime and criterion c

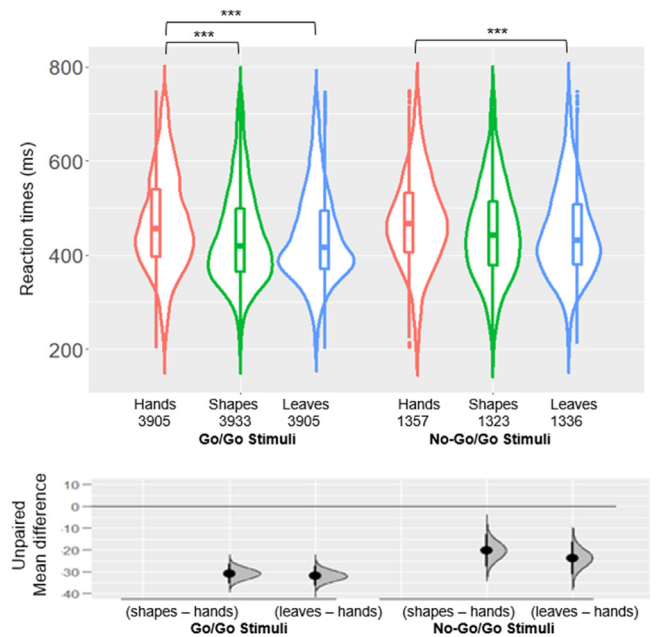
The results of an rm-ANOVA with a factor of Stimuli showed that neither the  $d'$  ( $F(2,76) = 0.721, p = .489, \eta_p^2 = 0.018$ ), nor the  $c$  was significantly different across the Stimuli conditions ( $F(2,76) = 0.416, p = .660, \eta_p^2 = 0.011$ ). In line with the results of Experiment 1,  $c$  values were slightly negative for all conditions (hands =  $-1.43$ , shapes =  $-1.46$ , leaves =  $-1.48$ ). The Bayes factor approach showed moderate evidence for a difference between Stimuli conditions for the  $d'$  ( $BF = 7015$ ) and moderate evidence for the criterion  $c$  ( $BF = 9.17$ ). The values of omissions and false rates can be found in the Supplementary materials.

### Reaction times of Go trials

We ran a generalized linear mixed model on Reaction Times of correct Go trials. As fixed effects, the best model included Stimuli (hand/shape/leaf) and Sequence (No-Go - Go / Go - Go) with interaction. As random effects, the model included slopes for Stimuli and Sequence and intercepts for Participants (i.e., it was the model with the maximal random structure justified by design (Barr et al., 2013)).

The simple effect of Stimuli significantly predicted the reaction times ( $\chi^2 = 48.06, df = 2, p = .001$ ) (Fig. 2c), showing that reaction times were slower for hand images ( $EM = 498, SE = 6.88$ ) compared to shape ( $EM = 475, SE = 9.01$ ; estimated difference  $B = 23.3, SE = 6.06, p = .001$ ) and leaf images ( $EM = 465, SE = 8.40$ ; estimated difference  $B = 33.4, SE = 7.12, p = .001$ ), while there was no significant difference between shape and leaf images (estimated difference  $B = 10.1, SE = 9.47, p = .53$ ) (Fig. 2). In contrast to the results of Experiment 1, the simple effect of Sequence was not significant ( $\chi^2 = 0.439, df = 1, p = .507$ ). However, the interaction between Stimuli and Sequence was significant ( $\chi^2 = 10.20, df = 2, p = .006$ ). Whilst reaction times were slower for Go trials preceded by a Go trial for hand images ( $EM = 499, SE = 6.97$ ) compared to both shape ( $EM = 469, SE = 8.83$ , estimated difference  $B = 30.20, SE = 5.65, p = .001$ ) and leaf images ( $EM = 463, SE = 8.89$ ; estimated difference  $B = 36.01, SE = 7.31, p = .001$ ), and not significantly different between shape and leaf images (estimated difference  $B = 5.82, SE = 9.04, p = .987$ ), reaction times were selectively slower for Go trials preceded by a No-Go trial for hand images ( $EM = 497, SE = 7.60$ ) only compared to leaf images ( $EM = 466, SE = 8.85$ ; estimated difference  $B = 30.79, SE = 7.85, p = .001$ ) and not to shape images ( $EM = 481, SE = 10.14$ , estimated mean  $B = 16.36, SE = 7.25, p = .211$ ) (see Fig. 3).

Overall, while the effect of Stimuli type was confirmed, we found that seeing right-hand images while using the same hand to respond slowed down Go trials preceded by a Go trial compared to leaf and shape images. The slower reaction times for hands compared to leaf and shape images found here confirms the results of Experiment 1 and indicates that the ability to resolve the conflict between Go and No-Go trials when dealing with hand images is more demanding than other non-body conditions. A Bayesian approach confirmed this pattern of results (see Supplementary Material).



**Fig. 3.** Reaction times and accuracy in the three Stimuli conditions (hand, shape, leaf) showing interaction stimuli and type of sequence (Go/Go, No-Go/Go) in experiment 2.

*Note.* (a) Panels show a violin and estimation plot (<https://github.com/ACCLAB/dabestr> (Ho et al., 2019), indicating significantly slower responses for hands compared to the other stimuli and the interaction with the sequence of the trial type (Go/Go or No-go/Go). Distributions of raw data are shown on top with summary measurements displayed as boxplots: the lines represent conventional mean (horizontal line)  $\pm$  standard deviation error bars. Below, the graphs show the effect size as mean difference, with 95% CI and its resampled distribution as curve (value zero is the mean for the hand category). \*\*\* means  $p < .001$ .

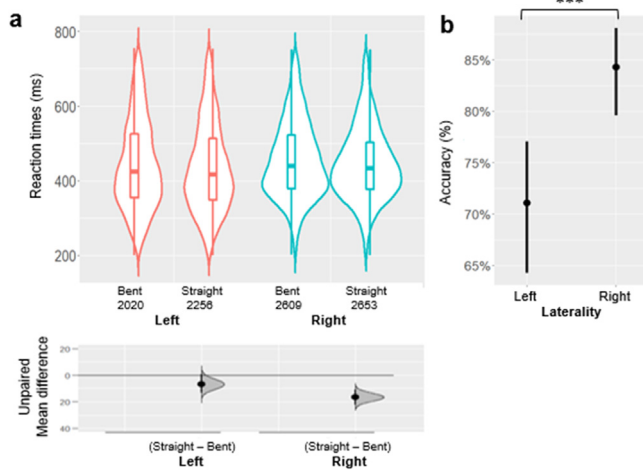
### Accuracy of responses of No-Go trials

We ran a generalized linear mixed model on the accuracy of No-Go trials. As fixed effects, the best model included Sequence. The model included slopes for Sequence and intercepts for Participants as random effects. The effect of Sequence was significant ( $\chi^2 = 5.03, df = 1, p = .025$ ), showing that accuracy was lower for No-Go trials preceded by a Go one ( $EM = 1.72, SE = 0.162$ ; 4154 sequences) compared to No-Go trials preceded by No-Go ones ( $EM = 1.97, SE = 0.178$ ; estimated difference  $B = -0.25, SE = 0.112, p = .026$ ; 1301 sequences).

Overall, the results on Accuracy replicated the pattern of Experiment 1 concerning the role of Sequence and did not confirm the marginally significant effect of Stimuli found in Experiment 1. This pattern of results suggests that the sensorimotor stimulus-response congruency does not interfere with inhibitory performance as the mere categorical congruency. A Bayesian approach confirmed this pattern of results (see Supplementary Material).

### Experiment 1 vs 2: comparing categorical and sensorimotor compatibility

In both Experiment 1 and 2, the two hand images used as Go stimuli presented a difference in the index finger, with one image showing a bent index finger and the other a straight index finger. Both experiments were planned to be as similar as possible to allow testing of a further hypothesis. We ran an additional analysis on RTs and Accuracy of response comparing the results of Experiment 1 and 2 in order to directly test whether the categorical and sensorimotor stimulus-response congruency affects the performance of the participants. We intended to test whether a higher compatibility between the hand observed and the hand used to respond, based on whether they are both right (Experiment



**Fig. 4.** Reaction times and accuracy in the two Congruency and two Position conditions between experiments 1 and 2.

*Note.* (a) Violin and Estimation plot (<https://github.com/ACCLAB/dabestr> (Ho et al., 2019)) indicates significantly slower responses for hands with the index finger bent compared to the images with the index finger straight. The graph below shows the effect size as mean difference, with 95% CI and its re-sampled distribution as a curve (value zero is the mean for the bent finger). (b) Plot showing accuracy measures for the Factor Congruency (Laterality). \*\*\* means  $p < .001$ .

2) or they are one left and one right (Experiment 2) (factor Stimulus-response Congruency), would result in a higher interference.

## Results

### *D-prime and criterion c*

We ran an independent sample Mann-Whitney  $W$   $t$ -test on the  $d'$  and found the main effect of Stimuli-response Congruency group not to be significant ( $W = 787.00$ ,  $p = .949$ ,  $r_{rb} = 0.009$ ). Regarding criterion  $c$ , we ran an independent sample Mann-Whitney  $W$   $t$ -test. A significant main effect of Stimuli-response Congruency group was found ( $W = 368.50$ ,  $p = .001$ ,  $r_{rb} = -0.528$ ) showing that the criterion was more liberal when responding to left hand (mean =  $-0.963$ ,  $SD = 0.527$ ) compared to right hand images (mean =  $-1.432$ ,  $SD = 0.413$ ).

### *Reaction times of Go trials*

We ran a generalized linear mixed model on correct Go trials from Experiments 1 and 2. As fixed effects, the model included Stimulus-response Congruency between seen and used hand (Experiment 1 no congruency, Experiment 2 congruency) and Position of the index finger (bent, straight) (with interaction). As random effects, the model included slopes for Congruency and Position of the index finger and intercepts for Participants.

The simple effect of Position of index finger was significant ( $\chi^2 = 7.13$ ,  $df = 1$ ,  $p = .008$ ), showing that reaction times were slower for images with the index finger bent (EM mean =  $491$ ,  $SE = 7.94$ ) compared to images with the index finger straight (EM =  $480$ ,  $SE = 8.17$ ; estimated difference  $B = 10.5$ ,  $SE = 3.91$ ,  $p = .007$ ). This effect was further modulated by the significant Stimulus-response Congruency  $\times$  Position interaction ( $\chi^2 = 4.75$ ,  $df = 1$ ,  $p = .029$ ) showing that reaction times were slower for the Go hand image with the index finger bent compared to straight only for right hands (EM =  $497$ ,  $SE = 10.19$  vs EM =  $479$ ,  $SE = 10.39$ ; estimated difference  $B = 17.91$ ,  $SE = 5.20$ ,  $p = .003$ ) and not for left hand Go images (estimated difference  $B = 3.12$ ,  $SE = 5.16$ ,  $p = .93$ ). All other comparisons were not significant ( $p > .05$ ) (Fig. 4).

This pattern of results indicates that the position of the index finger, bent or straight, generates a more decisive conflict resulting in a temporal cost only if the observed hand is congruent with the hand used to respond. A Bayesian approach confirmed this pattern of results (see Supplementary Material).

### *Accuracy of responses of No-Go trials*

We ran a generalized linear mixed model on No-Go trials from Experiment 1 and 2. As fixed effects, the best model included Stimulus-response Congruency. As random effects, the model included slope of Stimulus-response Congruency and intercepts of Participants. The simple effect of Stimulus-response Congruency was significant ( $\chi^2 = 11.77$ ,  $df = 1$ ,  $p = .001$ ), showing that accuracy was higher for right hands (EM mean =  $1.681$ ,  $SE = 0.163$ ) compared to left hand images (EM =  $0.899$ ,  $SE = 0.159$ ; estimated mean  $B = -0.782$ ,  $SE = 0.23$ ,  $p = .001$ ).

This pattern of results indicates that inhibiting right-hand responses while seeing right-hand responses is more accessible than seeing left-hand images: inhibitory processes are, therefore, more accurate for somatosensory congruent stimuli than mere categorical congruent stimuli, despite longer reaction times in both cases. A Bayesian approach confirmed this pattern of results (see Supplementary Material).

## Discussion

The present study investigated whether the bodily content of visual stimuli modulates cognitive control performance as measured through a go-no-go task, and whether inhibitory processes operate at a categorical representational level or they are sensitive to the specific sensorimotor representations putatively activated by the sight of body-related stimuli. By comparing body and non-body stimuli, the first experiment showed that 1) motor responses (Go trials) to body images take more time compared to those for non-body images, and 2) the ability to inhibit a motor response in No-Go trials is marginally reduced by the perception of a body image compared to non-body images. These findings suggest that body images can activate a categorical representation of the body that reduces the ability to resolve the conflict between responding and withholding to respond.

By increasing the level of congruency between the body images and the effector used to respond (i.e., right hand is perceived and used in motor response) experiment 2 confirmed the results of experiment 1 (body vs non-bodies differences) and expanded them by showing a stronger impact of trial sequence over RTs, but not over Accuracy of response.

By directly comparing the results of experiments 1 and 2 we sought to understand how categorical body representations (i.e., those activated by the mere sight of a body part, experiment 1) and specific sensorimotor body representations (i.e., those triggered by the sight of the hand congruent with that used to respond, experiment 2) affect the ability to inhibit a motor response and affect the time required to perform the response. This comparison showed that RTs were sensitive to the posture of the finger only when perceiving a hand congruent with that used to respond. This pattern of results suggests that the conflict to be resolved is affected by the amount of sensorimotor congruency between the triggering stimuli and the effector used, showing how a lower degree of congruency – categorical – affects both reaction times and accuracy, while a higher degree of congruency – sensorimotor – still delays reaction times but does not affect accuracy. Overall, the present data suggest that both categorical congruency and lower-level sensorimotor Stimuli-response congruency affect inhibitory resources and cognitive control.

Contrary to the intuitive prediction that seeing a hand would result in faster responses following priming effect, we think that these results suggest that the additional elaboration processes for hand images may result in a temporal cost reflecting the effort of the cognitive control system to cope with a greater conflict generated by the activity of extended visual, somatic and motor networks (Barsalou, 2008;

Brass et al., 2000). In this view, the resources needed to process the perceived hand (with different laterality and a different posture) and those needed to perform the response may conflict and thus slow down reaction times. The higher accuracy for right hands compared to left hands might reflect the increased effort required to process body images compatible with the effector used, resulting in fewer errors, as predicted by the conflict monitoring hypotheses (Botvinick et al., 2001). We propose that the present results suggest that also simulative and embodied processes, activated by the bodily content of the stimuli and the overlap with the body part used to respond, play a role in modulating inhibitory resources (Hommel, 2015b; Hommel et al., 2001). While previous evidence showed the effects of body and non-body-related visual stimuli beyond perception, into visual encoding and working memory mechanism (Galvez-Pol et al., 2018a; Galvez-Pol et al., 2018b) one possibility for the interpretation of the findings of our study is that they result from a combined impact of higher cognitive body category representations – i.e., what might be interpreted as a “categorical hypothesis” – and that of lower-level body representations – i.e., what might be interpreted as a “sensorimotor hypothesis” – over motor inhibitory processes. Another possibility is that they result from a graded similarity between the stimulus and the response effector. However, further research is required to understand the nature and extent of the relation between embodied simulations and cognitive control mechanisms and disentangle the mechanism behind the found effects. Alternative interpretations may be drawn from the results, such as for example a matching between observed and dominant hand. Indeed, since participants were right-handed and the instructions asked the participants to respond with their right index finger, we can not exclude that the motor performance could be biased by the use of the preferred hand to perform the task rather than only on the stimulus-response matching. Future studies might disentangle this issue by having participants answering with their preferred and un-preferred hand to both left- and right-hand images. Also, a basic effector-specificity or a facilitatory effect of pre-activating the hand representation could produce the results without generalizing to a complete grounding of cognitive control.

We are aware that our study has some limitations. First, as an online study, we could not control the environment in which participants performed the task or if they complied with the task instructions (i.e., responding with the indicated hand/finger). This is a known problem of online testing, which we tried to control by inserting specific instructions on how to perform the task and by including a performance check. Second, the samples were recruited differently. Experiment 1 recruited university students who participated for course credits, while Experiment 2 participants were recruited by the online platform and participated for money. Finally, as discussed above, a possible variable affecting the results is the hand dominance of the participants, which requires careful sample selection in future studies. Nevertheless, the main findings on slower reaction times and lower accuracy for hands compared to non-body stimuli were consistent across studies.

The pattern of results raises new questions for future studies. Such studies may investigate the top-down or bottom-up nature of the modulation of inhibitory resources by the body content of the stimuli, the role of context and awareness, which are crucial factors modulating cognitive control, or the effect of embodiment on cognitive control using different body parts. Specifically, the comparison between the effects of using different body parts (e.g. hand, foot, head) as stimuli could help disentangle categorical and sensorimotor impact over the stimulus-response interference.

## Overall conclusions

Our experiment showed that the bodily content of stimuli, compared to non-body stimuli, affects top-down control processes of behavioural inhibition. Our results support the proposal that cognitive control processes should be interpreted as grounded in contextual information and

associated with the stimuli and situations they are requested to act upon (Abrahamse et al., 2016; Braem and Egner, 2018).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.crbeha.2023.100108.

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