

# Same Action, Different Meaning: Neural Substrates of Action Semantic Meaning

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## Abstract

Voluntary actions are shaped by desired goals and internal intentions. Multiple factors, including the planning of subsequent actions and the expectation of sensory outcome, were shown to modulate kinetics and neural activity patterns associated with similar goal-directed actions. Notably, in many real-world tasks, actions can also vary across the semantic meaning they convey, although little is known about how semantic meaning modulates associated neurobehavioral measures. Here, we examined how behavioral and functional magnetic resonance imaging measures are modulated when subjects execute similar actions (button presses) for two different semantic meanings—to answer “yes” or “no” to a binary question. Our findings reveal that, when subjects answer using their right hand, the two semantic meanings are differentiated based on voxel patterns in the frontoparietal cortex and lateral-occipital complex bilaterally. When using their left hand, similar regions were found, albeit only with a more liberal threshold. Although subjects were faster to answer “yes” versus “no” when using their right hand, the neural differences cannot be explained by these kinetic differences. To the best of our knowledge, this is the first evidence showing that semantic meaning is embedded in the neural representation of actions, independent of alternative modulating factors such as kinetic and sensory features.

**Keywords:** fMRI, goal-directed actions, intention, MVPA, semantic meaning

## Introduction

Biological agents interact with the world through execution of goal-directed actions that are geared toward achieving desired outcomes. However, in many cases, the mapping between specific actions (and corresponding motor commands) and achievement of desired outcomes, which can span multiple timescales and complexities, is nontrivial. And so, different desired outcomes can be reached by performing similar actions. For example, students can raise their hand in class to either ask a question or answer a question asked by the teacher. Although these two actions of raising the hand might share similar motor commands, they are geared toward different desired goals. Notably, studies show that such motor commands are not as similar as they seem: Their kinetics and corresponding neural activity in sensorimotor regions are affected by multiple factors including environmental context, expected sensory consequences, and planning of subsequent movement (Rosenbaum et al. 2012; Gallivan and Culham 2015; Krishnan-Barman et al. 2017).

The kinematic measures of similar actions are modulated by planned future movement. For example, the kinematic parameters of a common initial reaching phase are modulated according to different future movement that is planned (subsequent pour/drink

(Cavallo et al. 2016), future movement direction (Howard et al. 2015), or the size of the movement’s target object (Ansuini et al. 2015; Soriano et al. 2019). Similarly, the final target displacement location was shown to affect initial grip position in two-step actions (Cohen and Rosenbaum 2004; Rosenbaum et al. 2012). Social context is another factor that affects kinematic features of common reach-to-grasp actions. For example, wrist velocity and trajectory have been shown to vary when performed in isolation or with the presence of another agent (Becchio et al. 2010).

The behavioral measures of goal-directed actions are also modified by the expected sensory feedback. Recent studies have shown that the coupling of button presses with auditory sounds (compared with silent button presses) modulate subtle kinetic features such as applied force (Neszmélyi and Horváth 2017, 2018). At the neural level, it has been shown that the expected sensory outcome of an action modulates neural activity associated with the preparation to move. Recordings using electroencephalography (EEG) have shown that the readiness potential preceding button presses is modulated by the expectation and probability of coupled auditory outcome (Reznik et al. 2018; Wen et al. 2018). Furthermore, functional magnetic resonance imaging (fMRI) findings demonstrate that neural responses in the

motor and the parietal cortex during execution of similar hand movements depend on the coupled visual consequences of these movements (Eisenberg et al. 2011; Krasovsky et al. 2014). For example, the neural activity associated with horizontal hand movements in the superior parietal lobule (SPL) and the motor/premotor cortex has been shown to encode the coupled movement direction of a visual cursor (Krasovsky et al. 2014). Such modulation of neural activity by coupled sensory consequences is well conceptualized by predictive coding theories suggesting that, as part of the motor commands associated with action execution, a corollary discharge induces an embodied simulation of the action's intended sensory outcome (Wolpert et al. 1995; Miall and Wolpert 1996; Wolpert and Flanagan 2001; Tian and Poeppel 2010). Together, these studies demonstrate that various factors can affect both behavioral and neural measures associated with seemingly similar actions.

Yet, alongside the sensory consequences, context or future plans, actions with similar motor or sensory properties can also differ in their semantic meaning. Accordingly, the same act of raising the hand in a general assembly could indicate a vote in favor or against a given proposition. However, whether and how the semantic meaning of an action modulates associated behavioral and neural measures are currently unknown. Therefore, in the current study, we used whole-brain fMRI and behavioral measures (response time [RT] and applied force measurements) to examine potential differences between two internal representations of an action's semantic meaning. We operationalize the term "semantic meaning of an action" by associating particular actions (button presses using a given hand) with "yes"/"no" answers to a binary question. By manipulating the mapping between an action and its underlying answer meaning, we examined the effect of semantic meaning on neural/behavioral measures associated with right- and left-hand button presses separately. Importantly, we controlled for known alternative modulating factors so to distill the effect of semantic meaning from other potential effects on action and its neural representation.

## Materials and Methods

### Participants

Twenty-six subjects (4 males, mean age 23.03, range 18–28 years) participated in a behavioral study, and 33 different subjects participated in an fMRI study. Two subjects did not complete the full scanning session due to discomfort in the scanner or difficulty in comprehending the experimenter's instructions, leaving data from 31 participants (16 males, mean age 26.7, range 19–34 years). All participants were healthy, right handed (self-report), had normal or corrected-to-normal vision, and were naïve to the purposes of the study. The studies conformed to the guidelines approved by the ethical committee in Tel-Aviv University and the Helsinki Committee of the

Sheba Medical Center. All participants provided written informed consent to participate and were compensated for their time.

### Experimental Design

The current study was set to examine how semantic meaning of actions—to express "yes" or "no"—is represented at the behavioral–kinetic as well as at the neural level. To this end, we employed a "yes"/"no" question paradigm such that subjects used similar actions to express different semantic meanings.

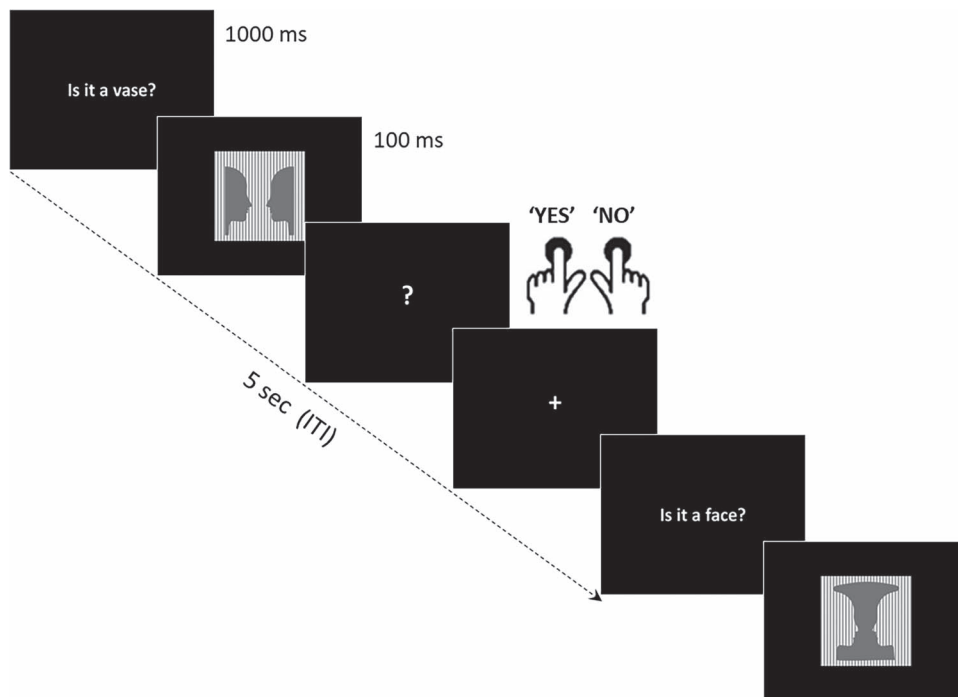
### Stimuli

Visual stimuli consisted of two images akin to the Rubin vase/face illusion. In each image, the object (vase/face) was uniformly colored over a striped background (as was used in Hasson et al. 2001). Although the two images share similar low-level visual features, at short presentations perception is predetermined and biased toward the colored object (either a face or a vase)—providing ground truth for the percept to be detected (see Fig. 1). Since the number of trials of face and vase images were balanced across all experimental conditions, the visual input was similar across the expected "yes"/"no" answers. Both the behavioral and the fMRI experiments were performed using Psychtoolbox-3 (Brainard 1997, [www.psychtoolbox.org](http://www.psychtoolbox.org)) on MATLAB 2016b (The MathWorks, Inc., Natick, MA, USA).

### Behavioral Experiment

Each trial began with the presentation of a question—either "Is it a face?" or "Is it a vase?" for 1 s, followed by a brief (100 ms) presentation of one of the two visual stimuli (vase or face). The stimuli were presented at the center of a monitor and subtended  $3.7^\circ \times 4^\circ$  visual angle. Following image presentation, a question mark appeared on the screen, cueing participants to provide their response (either "yes"/"no") at their own pace using either right- or left-hand button presses according to a predetermined mapping. Following participants' response, a fixation sign was presented at the center of the screen, for a duration completing a 5-s Inter Trial Interval (ITI) (see Fig. 1 for the experimental design).

The experiment included 4 runs of 80 trials each. In two runs, the right- and left-hand index fingers were mapped to "yes" and "no" answers, respectively, while the mapping was reversed in the other two runs. Run order was counterbalanced across participants. The different percepts and question types were counterbalanced such that, overall, within a particular hand there was no consistent difference in sensory input preceding expected "yes" and "no" answers. To ensure that participants correctly recalled the mapping between hand (right/left) and response ("yes"/"no"), they performed 20 practice trials before each run. Applied force was measured in the behavioral experiment using force sensors (FlexiForce™ A301, Tekscan Inc., Boston, MA, USA) with a dynamic range up to 4.4 N and repeatability of constant force



**Figure 1.** Experimental task design. Example trials of two out of the four question+percept combinations in the behavioral study. These example trials are taken from a right hand = “no”/left hand = “yes” hand mapping block and require a “NO” (right hand) response. Hand mapping is fixed once at the beginning of each behavioral block. The sequence of events is similar for the fMRI experiment (for exact time durations, see Material and Methods).

measurements of  $< 0.025$  N. The sensors were placed under two rubber buttons and connected to analog pins on Arduino® mega2560. The signal from each sensor was read using MATLAB Support Package for Arduino Hardware at a rate of 25 Hz. Press onset and offset were detected using a threshold of 0.28 N.

### fMRI Experiment

The experimental design of the fMRI study was similar to the behavioral study described above, with a few modifications. We used a longer ITI (12 s) and a shorter time for question presentation (900 ms). Subjects responded by pressing buttons on an MR-compatible response box using their thumbs. Subjects were required to respond within a time window of 2 s to maintain time-locking between subsequent stimulus presentation (size  $1.13^\circ \times 1.24^\circ$ ) and scanner acquisition time. No force measures were obtained in the scanner. Prior to each run, subjects performed 16 practice trials with the corresponding hand mapping to ensure correct mapping. Each experimental run contained 48 trials.

### fMRI Data Acquisition

Functional imaging was performed on a Siemens Magnetom Prisma 3T Scanner (Siemens Healthcare) with a 64-channel head coil at the Tel-Aviv University Strauss Center for Computational Neuroimaging. In all functional scans, an interleaved multiband gradient-echo, echo-planar pulse sequence was used. Whole-brain coverage was provided by acquiring 66 slices for each volume (slice thickness 2 mm; voxel size 2 mm isotropic; time to repetition (TR) = 1000 ms; time to echo (TE) = 30 ms;

flip angle =  $82^\circ$ ; field of view = 192 mm; acceleration factor = 2). For anatomical reference, a whole-brain high-resolution T1-weighted scan (slice thickness 1 mm; voxel size 1 mm isotropic; TR = 2530 ms; TE = 2.99 ms; flip angle =  $7^\circ$ ; field of view = 224 mm) was acquired for each participant.

### Data Analysis

#### Behavioral Data

To compare behavioral measures between “yes” and “no” answers, we examined the differences in delay between cue (appearance of question mark) and participants’ response (RT). RTs were log transformed for statistical comparison. In the behavioral experiment, we also compared the differences in button-press peak force and in the area under the curve (AUC) of the force time course across conditions. Each of these dependent measures was analyzed using a two-way repeated measures analysis of variance (ANOVA) with hand (right/left) and response type (“yes”/“no”) as within-subjects variables. Significant interactions were further probed using post hoc pairwise comparisons and corrected for multiple comparisons using a Bonferroni correction within participant, error trials were excluded from analysis, if present. Behavioral data were analyzed using SPSS Statistics version 27 (IBM) and JASP (JASP Team 2020, Version 0.14.1) was used for Bayesian analysis when required.

#### fMRI Data

fMRI data preprocessing was conducted using the FMRIB’s Software Library’s (FSL v5.0.9) fMRI Expert Analysis Tool (FEAT v6.00) (Smith et al. 2004). The data

from each experimental run underwent the following preprocessing procedures: brain extraction, slice-time correction, high-pass filtering at 100 s (0.01 Hz), motion-correction to the middle time point of each run, and correction for autocorrelation using prewhitening (as implemented in FSL). Trials with head motion that exceeded 2 mm were excluded from further analysis (max eight trials within a subject). All images were registered to the high-resolution anatomical data using boundary-based reconstruction and normalized to the Montreal Neurological Institute (MNI) template using nonlinear registration. Anatomical regions were identified using the Harvard-Oxford cortical structural atlas and the Automated Anatomical Labeling (AAL) atlas.

### Multivariate Testing Analysis

To detect differences in spatial patterns of activity across conditions, we used a nondirectional *multivariate testing* approach (MVPA Multi-t) (Gilron et al. 2017). Unlike *decoding* approaches, which involve building a model based on a subset of data (train set) and assigning a probabilistic label on the data that was set aside (i.e., prediction on the test set), in a *testing* approach, no model is built and the entire data set is used to examine differences between conditions. This latter approach is akin to an expansion of the standard univariate *t* test to the multivariate case, where a single trial sample is a vector of signals from multiple voxels rather than a single voxel. We chose the Multi-t testing approach since it has been shown to have better statistical power relative to decoding methods of multivariate signals (Rosenblatt et al. 2021).

For each voxel and each trial, we calculated activity level as the percent signal change relative to the time course mean. Since the hemodynamic response reaches peak approximately 5–6 s following event onset, in each trial we took the percent signal change of the blood oxygenation level-dependent (BOLD) signal in the fifth TR from the button-press onset (TR = 1 s).

For each voxel, defined as a center voxel, we outlined a neighborhood that included the center voxel and its 26 closest voxels using Euclidean distance. The activity pattern of a single trial was thus a vector of the activity level of all voxels in the neighborhood.

Compatible with the number of trials, we obtained for each center voxel 192 activity patterns across all experimental conditions (48 for each combination of hand and semantic meaning). The number of trials within conditions varied slightly across participants due to error trials (slow answers or using the wrong hand) and trials with excessive movement in the scanner that were excluded from analysis. To keep the trial number identical for statistical comparisons across conditions, within each participant, we randomly sampled *N* trials from conditions with more trials, where *N* represents the number of trials in the condition with least number of trials for that subject.

The pattern of activity levels of trials from different conditions was compared using the Multi-t analysis and each central voxel was assigned with a corresponding multivariate *t* value. Finally, this comparison was performed with a whole-brain searchlight approach (Krasovsky et al. 2014), such that each voxel in the brain was treated as center voxel once, and assigned a multivariate *t* value accordingly.

To assess the statistical significance of the multivariate *t* value, we compared it with a null distribution, which was generated by repeating the analysis with trial labels that were randomly shuffled according to the relevant test (e.g., “yes”/“no”). Overall, for each statistical test performed for each participant (i.e., right hand vs. left hand, “yes” vs. “no” answers in right-hand trials, “yes” vs. “no” answers in left-hand trials), we obtained a single map of Multi-t values based on the original data, and 400 maps of *t* values based on the randomly shuffled label data. To determine the group-level significance, we used the permutation scheme suggested by Stelzer et al. 2013. First, we averaged all the real statistical maps across subjects to create a group average map. Next, we randomly chose one shuffle map from each participant and averaged those shuffled maps across participants to create one average shuffled map. We repeated this procedure, creating an average map according to shuffled labels, 10 000 times, providing a distribution of shuffled *t* value maps (representing the null hypothesis). Within each voxel we used the distribution of shuffled *t* values to compute a corresponding voxel-wise *P* value of the *t* value obtained in the real map (lowest possible *P* value 1/10 000). We then submitted these *P* values to false discovery rate (FDR) correction (Benjamini and Hochberg 1995), with  $q = 0.05$ , to create a binary map of significant voxels.

### General Linear Model Analysis

To further assess whether the voxels found sensitive to semantic meaning in our Multi-t results are modulated by RT, the fMRI data were also analyzed using a general linear model (GLM) with RT as a parametric predictor. The model included two parametric predictors of (mean centered) right-hand RT and left-hand RT. A conventional double gamma response function was convolved with each of the regressors to account for the shape of the hemodynamic response. In addition, six motion parameter estimates from the rigid body motion correction were included in the model as nuisance regressors. We calculated right-hand RT > rest and left-hand RT > rest contrasts. Results from these contrasts were corrected for multiple comparisons using familywise error rate (FWE) with  $\alpha = 0.05$ .

## Results

### Behavioral Study

The results of the behavioral study showed high performance levels on the task, with all participants

**Table 1.** Statistical results—behavioral experiment

	Predictors	$f(1,25)$	$P$	$\eta^2$
Log (RT)	Hand	9.41	0.005	0.27
	Semantic meaning	109.20	0.000	0.81
	Hand * Semantic meaning	8.19	0.008	0.25
Force peak	Hand	92.00	0.000	0.78
	Semantic meaning	0.31	0.584	0.01
	Hand * Semantic meaning	0.01	0.924	0.00
Force AUC	Hand	17.36	0.000	0.41
	Semantic meaning	0.05	0.827	0.00
	Hand * Semantic meaning	0.77	0.388	0.03

Summary of the two-way repeated measures ANOVA results for each of the three behavioral measures in the behavioral study: RT, force peak, and AUC.

having at least 80% correct percept identification, and most of them having more than 95% correct trials (median = 96.3%, range: 80.0–99.7%). This is compatible with the proportion of correct answers reported previously with similar stimuli (Hasson et al. 2001, in which participants had an average of 96% of correct identification).

All behavioral measures were analyzed using a two-way repeated measures ANOVA with hand (right/left) and semantic meaning (“yes”/“no”) as within-subjects variables. Main effects of both hand and semantic meaning were found for log-transformed RT, such that right-hand answers were faster compared with left-hand answers ( $0.86 \pm 0.03$  vs.  $0.90 \pm 0.03$  s;  $F[1,25] = 9.41$ ,  $P = 0.005$ ) and “yes” answers were faster than “no” answers ( $0.81 \pm 0.02$  vs.  $0.94 \pm 0.03$  s;  $F[1,25] = 109.2$ ,  $P < 10^{-3}$ ). In addition, an interaction was found between hand identity and semantic meaning ( $F[1,25] = 8.19$ ,  $P = 0.00$ ) such that within the right hand, “yes” RTs were shorter than “no” ( $0.75 \pm 0.03$  vs.  $0.97 \pm 0.03$  s;  $t[25] = 8.05$ ,  $P < 10^{-3}$ , Bonferroni corrected), while in the left hand, no significant difference was found (“yes” =  $0.87 \pm 0.03$  s; “no” =  $0.93 \pm 0.03$  s;  $t[25] = 1.7$ ,  $P = 0.10$ ; for full statistical results, see Table 1).

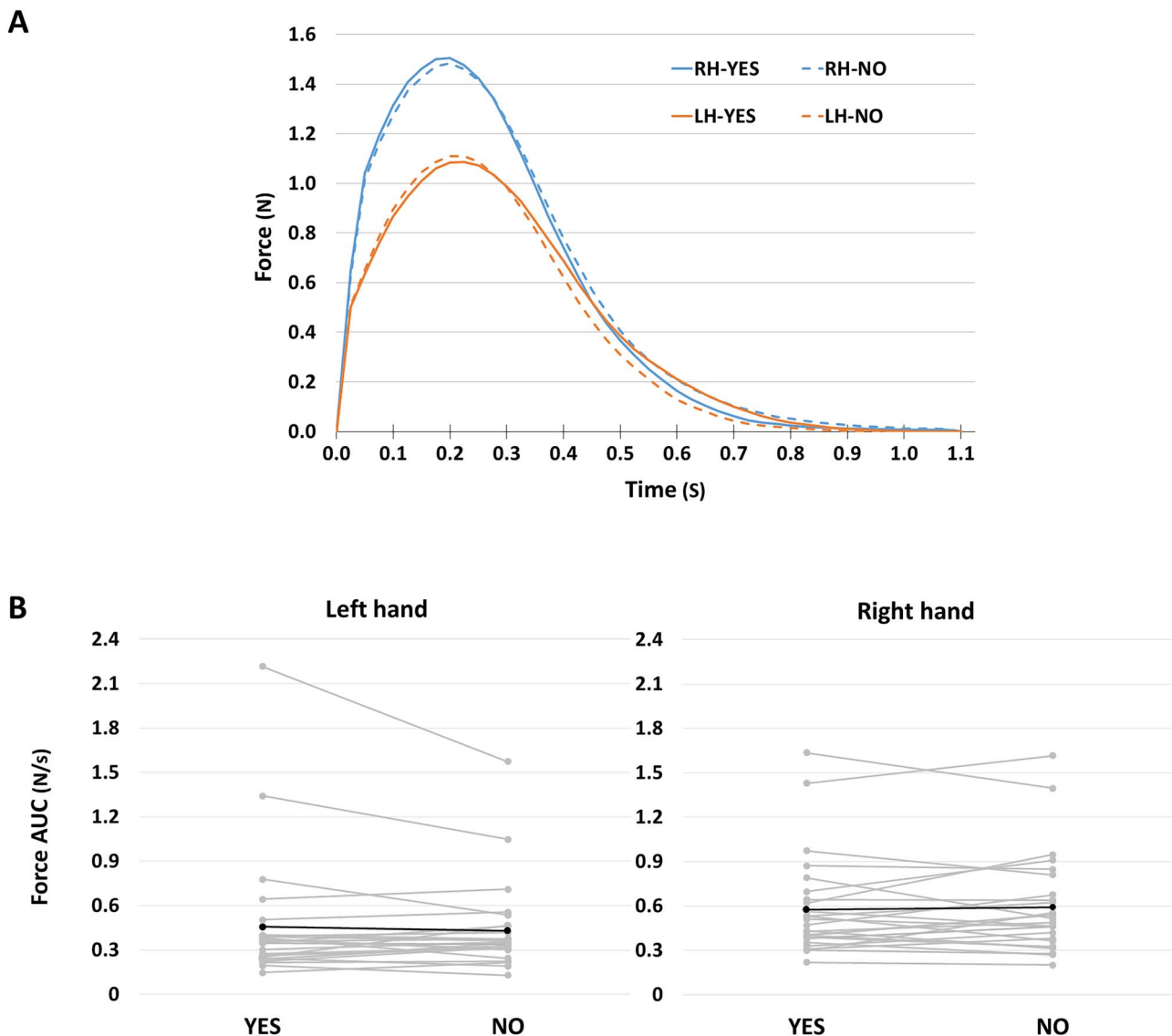
With respect to force measures, a significant effect was found for hand identity such that right-hand force peak and AUC were greater compared with the left hand (peak:  $1.78 \pm 0.13$  N vs.  $1.28 \pm 0.14$  N;  $F[1,25] = 92$ ,  $P < 10^{-3}$ , AUC:  $0.58 \pm 0.06$  vs.  $0.45 \pm 0.07$  N/s;  $F[1,25] = 17.36$ ,  $P < 10^{-3}$ ; see Fig. 2). No significant main effect for semantic meaning or interactions was found in force measures (see Fig. 2 and Tables 1 and 2 for a complete description of the behavioral results). In addition, results from Bayesian paired sample t test analysis show that within each hand, participants exert similar force for the two semantic meanings. This was found both in force peak (right-hand  $BF_{01} = 4.15$ , left-hand  $BF_{01} = 3.62$ ) and AUC (right-hand  $BF_{01} = 4.69$ , left-hand  $BF_{01} = 4.46$ ). These results suggest that within hand, the action’s semantic meaning do not modulate force measures of the executed action.

## fMRI Study

The behavioral measures of subjects in the fMRI study were compatible with those obtained in the behavioral study. Participants in the scanner had above 89% correct percept identification (median = 97.4%, range: 89.5–100%). A two-way repeated measures ANOVA of their log-transformed RTs showed a main effect for semantic meaning, such that “yes” answers were faster than “no” answers ( $0.80 \pm 0.03$  vs.  $0.90 \pm 0.04$  s;  $F[1,30] = 142.72$ ,  $P < 10^{-3}$ ), and a hand  $\times$  semantic meaning interaction ( $F[1,30] = 26.41$ ,  $P < 10^{-3}$ ). Post hoc analysis showed that in right-hand trials, “yes” answers ( $M = 0.73$  s, standard deviation [SD] = 0.03) were faster than “no” answers ( $M = 0.94$  s,  $SD = 0.04$ ;  $t[30] = 7.74$ ,  $P < 10^{-3}$ , Bonferroni corrected), while no differences were found in left-hand trials (“yes,”  $M = 0.85$  s,  $SD = 0.04$ ; “no,”  $M = 0.85$  s,  $SD = 0.03$ ;  $t[30] = 0.37$ ,  $P = 0.710$ ; see Table 3 for statistical results).

With respect to imaging data, we first performed MVPA Multi-t analysis contrasting right- and left-hand trials, collapsed across “yes” and “no” answers to detect center voxels sensitive to the responding hand (right/left). As expected, results from this analysis revealed significant voxels in the motor strip in the precentral and postcentral gyrus (light blue voxels in Fig. 3). Next, to test for sensitivity for semantic meaning, we compared activity patterns evoked by button presses representing “yes” versus “no” answers separately within each hand. The number of trials within conditions varied slightly across participants (range: 34–48 trials) but was balanced when conditions were compared (see Materials and Methods). Within right-hand answers, we found significantly different activity patterns for “yes” versus “no” answers in the right inferior frontal gyrus (IFG), the premotor cortex in bilateral precentral gyrus, left SPL, left angular gyrus, bilateral fusiform gyrus, and in the inferior lateral occipital complex (LOC) bilaterally ( $P < 0.05$  FDR corrected, see Fig. 3 and Table 4 for coordinates). For the left-hand trials, a similar analysis of pattern separation based on semantic meaning did not yield voxels that survived correction for multiple comparisons. However, using a more liberal threshold ( $P < 10^{-4}$  uncorrected) revealed voxels in locations adjacent to the ones found for the right hand, in the left premotor cortex and left SPL and voxels that overlapped with those found for right-hand trials in the inferior LOC bilaterally (see Fig. 4).

In principle, the differences we find in neural activity patterns for “yes” versus “no” answers in these regions could be ascribed to differences in right-hand RT we found at the behavioral level. To address this potential alternative source for our “yes”/“no” separation, we additionally performed the same Multi-t analysis, testing for differences in the neural activity patterns due to RTs rather than semantic meaning. For each participant, within each hand, trials across all runs were categorically separated to fast/slow according to RT speed using median split analysis, irrespective of the semantic meaning of the trial (i.e., “yes”/“no”). The analysis did not reveal



**Figure 2.** Applied force for “yes” and “no” answers in the right and the left hands. Group average force profiles (A), and individual subject’s AUC (in gray lines; group average in black) (B) of “yes” versus “no” answers within each hand, collapsed over sensory input. Greater force was applied in right-hand answers compared with left (\*\* $P < 0.001$ ), while no difference was found in force levels between the two semantic meanings within each hand. RH/LH corresponds to right hand and left hand, respectively.

**Table 2.** Descriptive measures—behavioral experiment

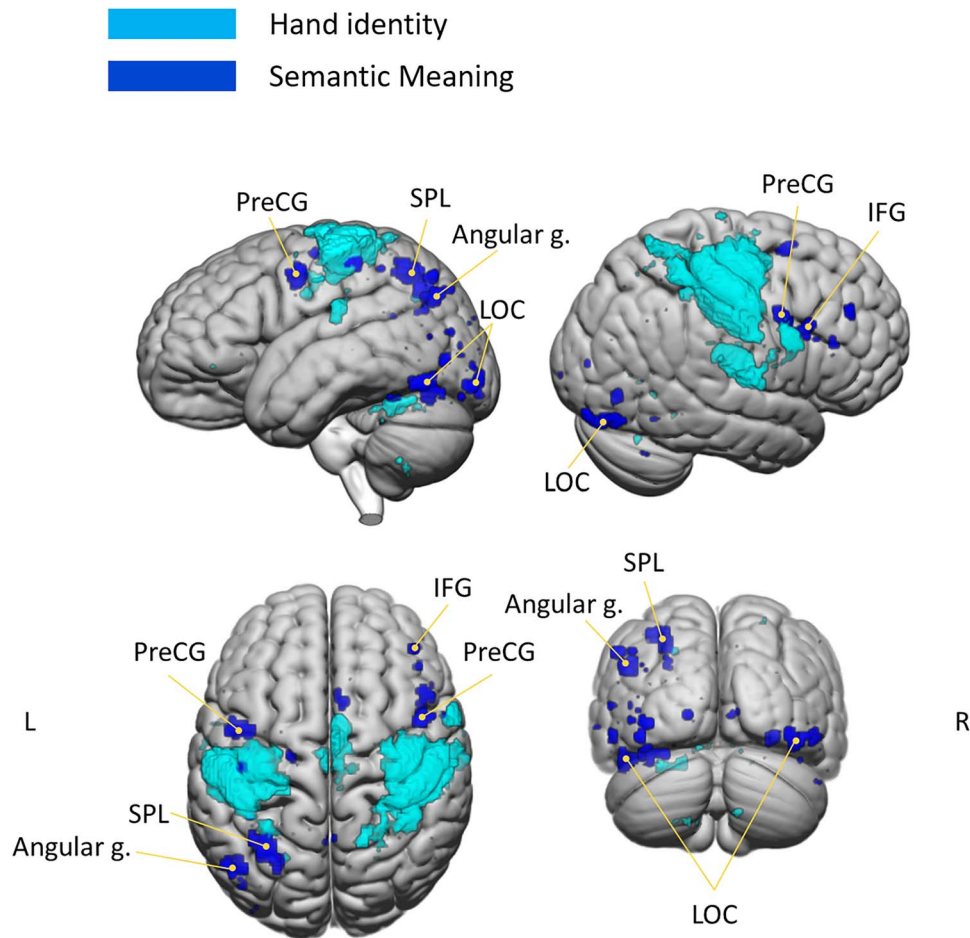
	RT(s)		Force peak (N)		Force AUC (N/s)	
	“Yes”	“No”	“Yes”	“No”	“Yes”	“No”
Right hand	0.75 (0.026)	0.97 (0.035)	1.80 (0.15)	1.77 (0.14)	0.57 (0.07)	0.59 (0.07)
Left hand	0.87 (0.034)	0.93 (0.030)	1.30 (0.17)	1.27 (0.13)	0.46 (0.08)	0.43 (0.06)

Estimates (mean, with SE in parentheses) of all experimental conditions for the three behavioral measures in the behavioral study: RT, force peak, and AUC.

significant voxels of separation between fast and slow trials, nor an overlap with the areas found sensitive to semantic meaning for right-hand trials, even when using a more liberal threshold of  $P = 10^{-4}$ , uncorrected. This is despite the biased proportion of yes answers in the fast trials (69.2% “yes” answers in fast trials). To further examine whether the activity in voxels showing significant “yes”/“no” separation in the MVPA is modulated by RT, we

also conducted a GLM analysis with RT as a parametric modulator (see Materials and Methods). No significant voxels with RT modulation were found. Together, these results support the notion that RT is an unlikely source of separation in the voxels found in the original “yes”/“no” analysis.

Another potential source for the neural differences we find for “yes”/“no” answers could be differences in the



**Figure 3.** Multi-t results: Areas sensitive to hand identity and semantic meaning. Differential neural activity for hand identity (right vs. left; light blue) in primary motor and supplementary motor area—precentral and postcentral gyrus, bilaterally. Differential neural activity for “yes” versus “no” answers, in right-hand trials (dark blue), in right IFG, premotor cortex—precentral and middle frontal gyrus bilaterally, left angular gyrus, left SPL, and bilaterally in the LOC and fusiform gyrus.  $P < 0.05$  FDR corrected.

**Table 3.** Statistical results—RT analysis fMRI experiment

	Predictor	$f(1,25)$	$P$	$\eta p^2$
Log (RT)	Hand	3.05	0.091	0.09
	Semantic meaning	142.72	0.000	0.83
	Hand * Semantic meaning	26.41	0.000	0.47

Summary of the two-way repeated measures ANOVA results for subject’s RT inside the scanner.

force applied during button presses. Although we did not measure press force in the scanner, this account is less likely since in the behavioral study we found no significant difference in press-force for “yes”/“no” answers within each hand (see Fig. 2). Therefore, taken together, the imaging results suggest top-down modulation of the lateral occipital, parietal, and premotor regions, according to the semantic meaning of the action, beyond action kinetics and immediate sensory consequences.

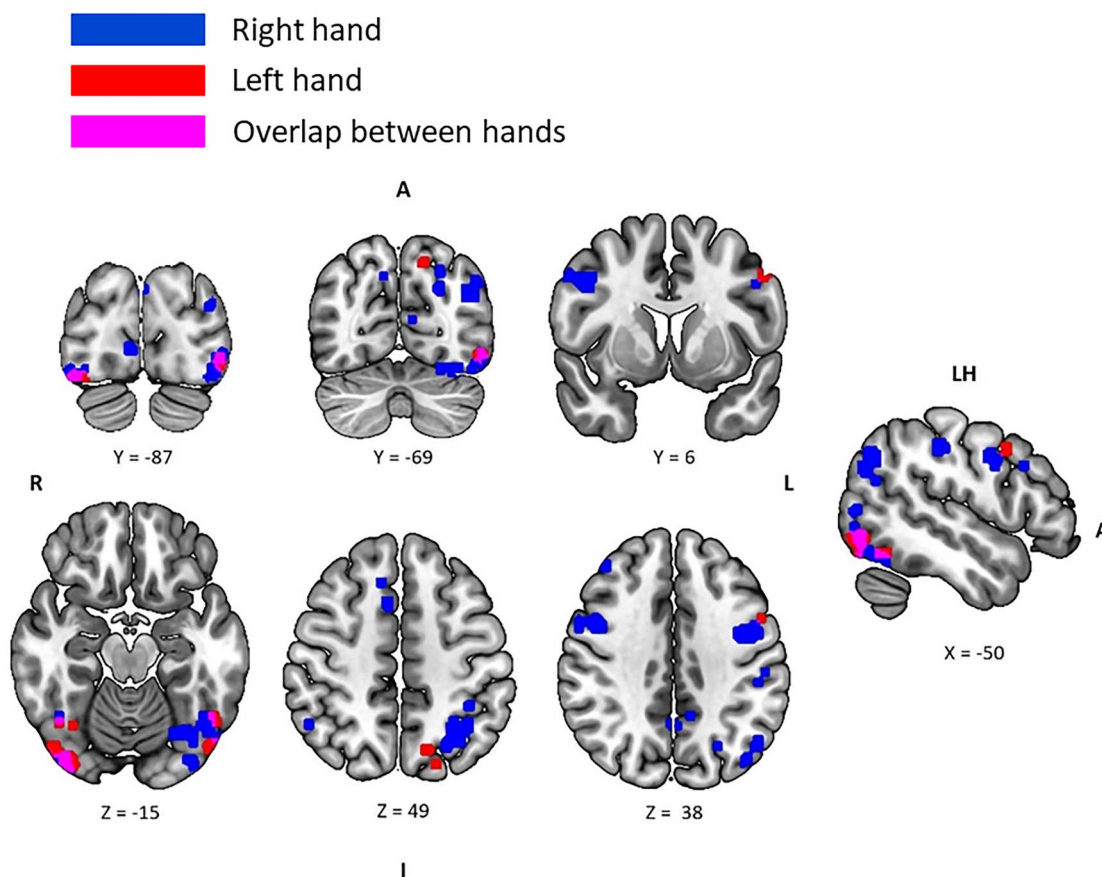
Finally, we examined whether the neural representation of the action’s semantic meaning is similar across hands, or rather hand dependent. To this end, we used a support vector machine (SVM) classifier (Chang and Lin 2011) with a 2-fold cross-validation. The classifier

**Table 4.** Coordinates of regions discriminating “yes” versus “no” semantic meaning

Structure	MNI coordinates		
	x	y	z
Right IFG	46.8	16	30.4
Left precentral G.	-44	-2	36
Right precentral G.	46	6	38
Left SPL	-32	-58	50
Left angular G.	-46	-68	32
Left fusiform G.	-38	-68	-16
Right fusiform G.	30	-74	-10
Left inf_LOC	-37	-91	-11
Right inf_LOC	42	-84	-14

Center positions (in MNI coordinates) of significant areas sensitive to semantic meaning in right-hand trials ( $P < 0.05$  FDR corrected).

was trained to discriminate activation patterns from “yes”/“no” trials based on data from right-hand trials and tested on “yes”/“no” activation patterns from left-hand trials. This analysis was conducted on all significant right-hand voxels that were found in the Multi-t analysis described earlier. Resulting accuracy values of this cross-decoding analysis (accuracy range across voxels:



**Figure 4.** Areas sensitive to semantic meaning in right and left hands. Significant areas in which neural activity differentiates “yes” versus “no” answers in right-hand trials (blue,  $P < 0.05$  FDR corrected, similar to Fig. 3). Adopting a liberal threshold in left-hand trials reveals adjacent areas in left premotor cortex and left SPL (red,  $P < 10^{-4}$  uncorrected) and overlapping areas in the LOC bilaterally (magenta).

0.45–0.53%) were not significantly higher than the baseline distribution generated by the same analysis performed on shuffled data labels (0.49–0.50%). This suggests that the “yes”/“no” activity patterns in right-hand trials are different from “yes”/“no” activity patterns in left-hand trials.

## Discussion

In the current study, we examined whether and how neurobehavioral measures of similar actions are affected by different semantic meaning. Behavioral measures indicate that within each hand, subjects applied similar force levels for the two semantic meanings (“yes”/“no”). With respect to RTs, subjects tended to be faster when responding “yes” than “no” across the two experiments. Our fMRI results show that different semantic meanings (“yes”/“no” answers) modulate neural activity patterns in sensory–motor areas in frontoparietal and occipital cortex. Specifically, for right-hand trials, a significant separation of “yes” versus “no” answers was found in the bilateral premotor cortex, right IFG, left angular gyrus, left SPL, inferior LOC, and fusiform gyrus bilaterally. Similar regions were also found for left-hand trials, although statistically weaker. Importantly, the differences in neural patterns are not explained by differences in RT.

Faster “yes” than “no” responses were previously reported when subjects were engaged in a speeded reaction time task (Wentura 2000). In the current experimental design, we did not employ a speeded reaction task, and subjects responded at their own pace. In the fMRI study, subjects were constrained to respond within a 2-s time window to remain in sync with scanner timing. However, this time window is much longer than the typical RT of  $\sim 500$  ms in the behavioral study. Thus, even when not engaged in a speeded response task, subjects are faster to respond “yes” versus “no.” In principle, differences in RT could potentially explain differences in neural activity patterns for “yes”/“no” answers. Indeed, a previous study (Yarkoni et al. 2009) highlighted that the fMRI BOLD signal is correlated with reaction time in various gray and white matter regions of the brain. Therefore, we directly tested the regions found sensitive to semantic meaning in the current study for differences in neural activity based on RT. Using the same Multi-t analysis that revealed neural differences between “yes” and “no” answers, we directly compared the neural activity patterns of slow and fast RT trials (based on median split of response latencies). No significant voxels were found. Even at a more liberal threshold, there was no overlap in voxels sensitive to RT and those found sensitive to semantic meaning within the right-hand



trials. This was further supported by an additional GLM analysis we performed using a parametric predictor, based on single-trial RT, which did not reveal significant voxels either. Taken together, these analyses suggest that it is less likely that the differences found in the neural activity patterns for semantic meaning can be accounted for by differences in reaction time.

The areas we found sensitive to semantic meaning in the current study have been previously implicated in high-level representations of goal-directed actions during execution and observation (Hamilton and Grafton 2006; Wurm and Lingnau 2015; Gallivan et al. 2016; Gertz et al. 2017). For example, the motor, the premotor, and the posterior parietal cortex were shown to be similarly activated during action execution, observation, and presentation of action-related verbs (Pulvermüller et al. 2005; Kiefer and Pulvermüller 2012; Mollo et al. 2016; Aflalo et al. 2020). In addition, parieto-occipital regions were found sensitive to different grip types (whole-hand/precision grip), allowing successful decoding based on neural activity patterns (Turella et al. 2020). Activity patterns in these regions as well as in the premotor cortex were also shown to differentiate two movement directions during planning (Gallivan et al. 2011). Furthermore, neural activity in the lateral occipitotemporal cortex and intraparietal sulcus (IPS) was found to encode observed actions and objects in different levels of abstraction (Wurm and Lingnau 2015; Wurm et al. 2016). Finally, the motor, the premotor, and the parietal cortex were also found sensitive to the relationship between actions and their visual outcomes (Hamilton and Grafton 2008; Eisenberg et al. 2011; Krasovskiy et al. 2014). These findings indicate that frontoparietal and lateral-occipital regions represent different levels of goal-directed actions, from the motor act itself onto the action's sensory consequence. Importantly, however, in these studies, the semantic meaning of the action was not manipulated and actions were coupled with either different sensory or motor features (or both). In the current study, however, we show differential activity patterns in premotor cortex, SPL, LOC, and fusiform gyrus encoding the action's underlying semantic meaning that is not associated with different sensory and motor attributes of the action.

The spatial similarity between voxels differentiating “yes” versus “no” answers in right- and left-hand trials suggests that the two hands share a common neural substrate representing semantic meaning. This raises the possibility that the two hands might also share a common functional representation of semantic meaning. To address this question, we performed cross-classification, using SVM, within the voxels that were found sensitive to the semantic meaning of right-hand button presses. We trained a model on right-hand trials (“yes” vs. “no”) and examined classification of left-hand trials. Despite the spatial overlap of voxels discriminating “yes”/“no” responses in the two hands, our analysis did not yield significant cross-decoding. This implies that while these regions differentiate the intended meaning of the action

(“yes” vs. “no”) in both hands, they do so in a different manner for each hand. This seems to be at odds with previous studies reporting that during execution, neural activity patterns differentiating the action type (e.g., reach/grasp actions)—can be generalized across hands in the IPS (Gallivan et al. 2013a; Turella et al. 2020). Moreover, across-effector (i.e., hand/tool) generalization was evident in the IPS, as well as in premotor areas during action planning and execution (Gallivan et al. 2013b). In these studies, the differential activity patterns, which generalized across hands, were elicited for two different actions. Here, however, we manipulated the semantic meaning of similar actions while examining its effect on neurobehavioral measures. The current findings indicate that unlike categories of preformed actions, the neural representation of the action's overarching semantic meaning (to convey “yes” or “no”), is not shared across hands. This result is in line with previous findings showing that the perception and neural representation of sensory action consequences are differentially modulated by hand-identity (Reznik et al. 2014; Buaron et al. 2020). In other words, identical stimuli evoke differential activity patterns in sensory regions, according to the hand (right/left) that was used to generate them. It is thus possible that activity patterns associated with the semantic meaning encapsulate information regarding the effector being used to achieve it. This could imply a difference in neural organization between action categories and action semantic meaning; however, this issue needs to be directly examined in future studies.

A recent study examined semantic meaning of actions in the context of brain–computer interface by decoding “yes”/“no” answers based on EEG signals (Yoshimura et al. 2021). In this study, the authors used Pavlovian conditioning to associate different sensations (equilibrium distortion using galvanic vestibular stimulation) to “yes” and “no” answers. EEG-based “yes”/“no” decoding showed higher accuracies postconditioning compared with preconditioning. In addition, fMRI results showed activation difference between “yes” and “no” answers in similar regions found in the current study, including the angular gyrus, SPL, and precentral gyrus following but not prior to conditioning. Notably, in this study, the two semantic meanings were associated with different sensory experiences when subjects were answering “yes” and “no.” In the current study, “yes” and “no” answers were distinguished based on neural activity patterns in the absence of any difference in sensory attributes associated with the different semantic meanings.

Localizing the neural circuits that underlie action goal representation has implications for the development of more accurate and efficient brain–machine interfaces (Ortiz-Rosario and Adeli 2013; Rezeika et al. 2018; Yoshimura et al. 2021). Moreover, shedding light on the neural architecture of action organization and identifying the processes by which internal states are constructed into actions can inspire the development of computational models for human action understanding

and may provide insight with respect to pathologies such as apraxia in which action goal representation is compromised (Grafton and Hamilton 2007). Our current findings point to neural activity patterns in specific sensory-motor regions as neural substrates representing the semantic meaning of an action, thus, motivating the use of these regions as potential signal source for decoding genuine real-time human intentions to operate neuroprosthetics with increasing functionality.

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