Cognition 240 (2023) 105589

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Meaning in hand: Investigating shared mechanisms of motor imagery and sensorimotor simulation in language processing

Emiko J. Muraki [a,b,*], Stephan F. Dahm [c], Penny M. Pexman [a,b]

[a] Department of Psychology, University of Calgary, Canada
[b] Hotchkiss Brain Institute, University of Calgary, Canada
[c] Department of Psychology, Universität Innsbruck, Austria

ARTICLE INFO

Keywords:
Semantic representation
Grounded cognition
Motor imagery
Body-object interaction

ABSTRACT

There is substantial evidence to support grounded theories of semantic representation, however the mechanisms of simulation in most theories are underspecified. In the present study, we used an individual differences approach to test whether motor imagery may share some mechanisms with sensorimotor simulations engaged during semantic processing. We quantified individual differences in motor imagery ability via implicit imagery tasks and explicit imagery questionnaires and tested their relationship to sensorimotor effects in syntactic classification tasks. In Experiment 1 ($N = 185$) we tested relationships between motor imagery and semantic processing of body-object interaction meaning (BOI; the degree to which you can interact with a word's referent) and foot/leg action meaning. We observed two interactions between imagery ability measured on the Florida Praxis Imagery Questionnaire (FPIQ) and BOI effects in semantic processing (response time and accuracy). In both interactions poorer imagery ability was associated with null BOI effects, whereas better imagery was associated with BOI effects. We also observed faster and more accurate responses to verbs associated with more foot/leg action meaning than verbs with less foot/leg action meaning, but this foot/leg action effect did not significantly interact with individual differences in motor imagery. In Experiment 2 ($N = 195$) we tested whether the interactions observed in Experiment 1 were dependent on the object-directed nature of the actions, or whether similar effects would be observed for hand actions not associated with objects. We also expanded our investigation beyond hand and foot imagery to consider whole body imagery. We observed an interaction between performance on a hand laterality judgement task (HLJT; assessing hand motor imagery) and sensorimotor effects in semantic processing of verbs associated with hand/arm action meaning. Participants with the fastest responses on the most difficult trials of the HLJT showed no significant difference in their response times to words with high and low hand/arm action meaning. We also observed faster and more accurate responses to high relative to low embodiment verbs, but this sensorimotor effect did not interact with individual differences in motor imagery. The results suggest specific (and not general) associations, in that some, but not all forms of hand and object-directed motor imagery are related to sensorimotor effects in language processing of hand/arm action verbs and nouns describing objects that are easy to interact with. As such, hand and object-directed motor imagery may share mechanisms with sensorimotor simulation during semantic processing.

1. Introduction

Theories of grounded cognition (Barsalou, Santos, Simmons, & Wilson, 2008; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012) propose that mental representations such as those for concept knowledge (hereafter referred to as concepts), are at least partially constituted *in* simulations within sensorimotor and perceptual brain regions. This is in contrast to amodal theories, which propose that concept knowledge is represented in amodal brain regions (Fodor, 1975; Pylyshyn, 1980) that are engaged *ancillary to* sensorimotor and perceptual experience. Within psycholinguistics there are several theories (*Language and Situated Simulation*, Barsalou, 2016; Barsalou et al., 2008; *Words as Social Tools*, Borghi et al., 2017; *Linguistic Shortcut Hypothesis*, Connell, 2019; *Hub + Spoke Model of Semantic Memory*, Patterson & Lambon Ralph, 2016) which propose that concepts are grounded via simulation of sensorimotor, linguistic, and emotional experience (among others). Yet the

* Corresponding author at: University of Calgary, 2500 University Drive, Calgary, Alberta T2N 1N4, Canada.
E-mail address: ejmuraki@ucalgary.ca (E.J. Muraki).

https://doi.org/10.1016/j.cognition.2023.105589
Received 31 October 2022; Received in revised form 26 July 2023; Accepted 3 August 2023
Available online 9 August 2023

mechanisms for sensorimotor simulations (Barsalou, 2016) have been underspecified in most grounded theories of semantic representation. While it is assumed that sensorimotor simulation involves brain regions related to perception and action, it is unclear whether the simulations engage these regions in the same manner as online perception and action. For instance, it is unclear if they would show different patterns of activity across laminar layers of the cortex as has been observed with visual working memory, with the patterns corresponding to top-down recruitment of simulations vs bottom-up processing of perceptual information (Lawrence et al., 2018). Thus, clarifying the nature of sensorimotor simulation remains an important area of research to test inferences derived from theories of grounded cognition. In the present study we investigated whether better motor imagery ability is associated with more use of sensorimotor simulation during language processing, with the inference that these two processes share some mechanisms if a relationship is observed.

Grounded theories of semantic representation have been tested in single word processing using lexical decision tasks (e.g., is it a word or a nonword?), semantic decision tasks (e.g., is it an abstract or a concrete word?), and syntactic classification tasks (e.g., is it a noun or a verb?). A common finding in such tasks is that words strongly associated with sensorimotor experience are processed faster and more accurately than words less strongly associated with sensorimotor experience (e.g., faster processing for words with higher ratings on dimensions such as imageability, Cortese & Schock, 2013; concreteness, Goh, Yap, Lau, Ng, & Tan, 2016; sensory experience, Juhasz & Yap, 2013; body-object interaction, for noun stimuli, Pexman, Muraki, Sidhu, Siakaluk, & Yap, 2019; relative embodiment, for verb stimuli, Sidhu, Kwan, Pexman, & Siakaluk, 2014). One possible explanation for these findings is that word meaning is grounded to some extent in sensorimotor experience, and that simulations of sensorimotor experience are engaged during language processing (although for alternative explanations see Ostarek & Bottini, 2021). This inference is further supported by neuroimaging studies which find that conceptual processing is consistently associated with modality-specific activity in sensorimotor brain regions (Kuhnke, Beaupain, Arola, Kiefer, & Hartwigsen, 2022).

Motor imagery may share mechanisms with sensorimotor simulations during language processing (Cayol & Nazir, 2020; Grush, 2004). The *Motor Simulation Theory* (Jeannerod, 2006) proposes that motor imagery constitutes a covert mental execution of the early stages of action planning and appraisal, which is then suppressed before the physical execution occurs. This is supported by studies showing similar brain activation during action imagery and action execution (Lorey et al., 2013; Munzert, Lorey, & Zentgraf, 2009). Similarly, the *Motor-Cognitive Model of Motor Imagery* (Glover & Baran, 2017) proposes that motor imagery and motor execution are functionally and neurologically similar in the action planning stage, but that they diverge during the action execution and monitoring stage. In this model, motor imagery uses conscious executive control to maintain and monitor progress towards an action goal, whereas motor execution unconsciously applies visual and proprioceptive feedback to adjust during online action execution. Finally, *Emulation Theory* (Grush, 2004) proposes simultaneous emulation of motor planning, execution, and sensory feedback during motor imagery, using neural mechanisms to learn the relationship between an action and its sensory feedback in order to predict action consequences (Cayol, Rotival, Paulignan, & Nazir, 2020). Motor imagery literature often uses the term *simulation* to describe *conscious* mental representations that occur in motor neural regions during motor imagery, but it is unclear whether this overlaps with mechanisms of *simulation* during language processing, which are predominantly *unconscious and involuntary* (Willems, Toni, Hagoort, & Casasanto, 2009). It has been proposed that mechanisms that support motor imagery may be repurposed for sensorimotor simulation during language processing (Cayol & Nazir, 2020). This is consistent with theories of neural reuse wherein neural circuits for one purpose are often repurposed to other processes (Anderson, 2010) and an evolutionary perspective on grounded cognition, that our cognitive processes have developed from a foundation afforded by our sensorimotor systems (Wilson, 2008).

Simulation and imagery may vary between individuals (Dahm, 2020; Roberts, Callow, Hardy, Markland, & Bringer, 2008). Therefore, individual differences approaches present an opportunity for testing grounded theories of semantic representation, particularly with the emergence of theories which emphasize flexible processes that can be influenced by situational or individual variability (Barsalou, 2020; Ibáñez et al., 2022). These theories predict that individuals with better simulation skills should also have larger sensorimotor effects in language processing tasks. Yet only three studies have investigated individual differences in motor imagery and sensorimotor effects in language processing (Cayol et al., 2020; Muraki & Pexman, 2021; Pavan & Baggio, 2013) and their findings are inconsistent. In a verb phrase judgement task (does the phrase imply leftward or rightward motion), there was no correlation between sensorimotor effects and individual differences in self-rated vividness of motor imagery (Pavan & Baggio, 2013). In contrast, in a word definition task (is the word definition correct or incorrect), for words strongly associated with sensorimotor experience, accuracy was correlated with motor imagery duration (Cayol et al., 2020). These conflicting findings may be due to variability in the tasks used to elicit sensorimotor effects and in the measures used to quantify motor imagery ability (for an overview see Dahm, 2020). Moreover, Pavan and Baggio investigated sensorimotor grounding with visual motion after-effects and found no sensorimotor effect in verb phrase processing and no interaction between sensorimotor effects and motor imagery.

Muraki and Pexman (2021) found no correlation between composite measures of motor imagery ability (derived via exploratory factor analysis from several motor imagery questionnaires and assessments) and sensorimotor effects in lexical decision, syntactic classification, or sentence-picture verification tasks (where the task decision was to decide if a pictured object was mentioned in a preceding sentence). However, in exploratory analyses they identified a significant correlation between accuracy for hand position imagery based on scores from the Florida Praxis Imagery Questionnaire (FPIQ; Ochipa et al., 1997) and body-object interaction (BOI) effects in syntactic classification task (SCT) response latencies, wherein participants with better hand position imagery had larger BOI effects. The specificity of this correlation between hand motor imagery and BOI (a semantic dimension largely informed by how easily one can grasp the entity to which the word refers; Heard, Madan, Protzner, & Pexman, 2019) suggests that it is necessary to more thoroughly investigate the potential for shared mechanisms between hand motor imagery and BOI sensorimotor effects in semantic processing.

The present study was conducted to test potential interactions between individual differences in motor imagery and sensorimotor effects in semantic processing. We assume that sensorimotor effects reflect simulations of sensorimotor experience which aid in processing (e.g., Siakaluk et al., 2008). If interactions are observed, it would afford the inference that motor imagery and sensorimotor simulation share some mechanisms. In Experiment 1, we intended to replicate the BOI and FPIQ interaction on response times (Muraki & Pexman, 2021) and to extend the analysis to include response accuracy. Further, we expanded this line of inquiry to test the correlation between motor imagery and sensorimotor simulation in a different effector, based on prior research that language processing is associated with somatotopically-related neural activity (Hauk, Johnsrude, & Pulvermuller, 2004; Klepp et al., 2014). Motor imagery has also been associated with somatotopically-related neural activity in the motor cortex (Stippich, Ochmann, & Sartor, 2002), including effector-specific imagery for hands and feet (Ehrsson, Geyer, & Naito, 2003). We examined whether the ability to imagine and make laterality judgements for foot/leg actions is correlated with processing foot/leg-related action verbs. In Experiment 2, we tested the correlation between individual differences in motor imagery abilities and hand/arm sensorimotor information (hand/arm action strength ratings). We also broadened our investigation to test whether individual differences in motor imagery and sensorimotor effects in language processing generalize to the whole body (embodiment ratings).

We selected motor imagery measures to maximize sensitivity to individual differences in hand, foot, and full-body motor imagery ability. There are concerns about motor imagery questionnaires that measure imagery using participants' self-report, such as the potential for social desirability effects, overestimation of ability, and lack of self-awareness to provide accurate assessments of ability (Dahm, 2020). Measures that are not subject to these self-report biases include the mental body rotation task (MBRT; Dahm, 2020; Dahm, Muraki, & Pexman, 2022), the hand laterality judgement task (HLJT; Parsons, 1987) and final position selection tasks such as the Test of Ability in Movement Imagery (TAMI; Madan & Singhal, 2013). In the present studies, we used four objective motor imagery measures. The MBRT requires participants to make a left/right decision on human-like pictures that show either a hand/arm or foot/leg extended. The HLJT requires participants to make a left/right decision on hand forms. The MBRT and the HLJT both involve mental rotation, which is associated to a limited extent with vividness of visual imagery (Habacha, Molinaro, & Dosseville, 2014; Zhao & Sala, 2018). However, better MBRT performance has also been associated with motor expertise, suggesting that there is a component of motor imagery involved in this task (Steggemann, Engbert, & Weigelt, 2011). Furthermore, the left/right decisions in the MBRT and the HLJT encourage perspective taking, differing from the same/different decision typically employed in mental rotation tasks (Hoyek, Di Rienzo, Collet, Creveaux, & Guillot, 2014; Parsons, 1987) and therefore reducing the reliance on mental rotation to complete the task. The TAMI requires participants to select a final body position after imagining a series of actions. Finally, the FPIQ requires participants to imagine everyday actions and select the appropriate answer from two response options.

To test for sensorimotor effects in language processing, we used go/no-go SCTs, which have consistently been shown to be sensitive to semantic effects with English stimuli (Muraki & Pexman, 2021; Muraki, Sidhu, & Pexman, 2022; Sidhu et al., 2014). We manipulated sensorimotor characteristics of the stimulus words according to the research questions in each experiment. In Experiment 1, BOI was manipulated as a measure of object-related sensorimotor information. In the BOI SCT go trials were nouns and no-go trials were verbs (a direct replication of Muraki & Pexman, 2021). In the remaining three SCTs, we manipulated the sensorimotor characteristics of interest in verb stimuli to focus on action representations. The manipulated variables were foot/leg and hand/arm action strength ratings, which quantify the degree to which a word's meaning is associated with actions involving the named body parts (Lynott, Connell, Brysbaert, Brand, & Carney, 2020), and embodiment ratings (Sidhu et al., 2014), which quantify the degree to which a verb's meaning involves the human body. In these versions of the task, go trials were verbs and no-go trials were nouns.

2. Experiment 1

In Experiment 1 we tested the relationship between individual differences in motor imagery abilities and sensorimotor information related to effectors (quantified via BOI and foot/leg action strength ratings). If motor imagery and sensorimotor simulations during language processing rely on some of the same mechanisms (Cayol & Nazir, 2020; Grush, 2004), it was expected that we would observe 1) an interaction between scores on the FPIQ position subscale and BOI, such that individuals with higher scores (indicating better ability to imagine hand positions) would have more pronounced BOI effects during semantic processing, and 2) interactions between each of the motor imagery tasks (MBRT and TAMI) and foot/leg action strength verb processing, such that individuals with faster response times on foot MBRT trials (indicating better ability to imagine foot positions) would have more pronounced foot/leg action strength effects during semantic processing, as would individuals with higher TAMI scores (indicating more accurate motor imagery ability generally).

2.1. Method

2.1.1. Participants

One hundred and eighty-five participants (146 female, 35 male, 1 non-binary, 3 did not respond, *M* age = 21 years, *SD* = 4.2) completed this online study in exchange for psychology course credit at the University of Calgary. Of the sample, 154 were retained following our data cleaning procedures (127 female, 25 male, 1 non-binary, 1 did not respond, *M* age = 21 years, *SD* = 4.6). Of the retained sample, 107 participants reported that English was their first language.[1] Those reporting that English was not their first language reported being either completely fluent ($n = 34$), very fluent ($n = 8$), or somewhat fluent ($n = 4$). One participant did not report first language status. A sample size of $N = 158$ is required to achieve a stable correlation (90% confidence level with a 0.15 stability width as indicated in Schönbrodt & Perugini, 2013) at a small effect size ($r = 0.10$). A similar sample size ($N = 146$) has previously been shown to suffice for the proposed analyses (Muraki & Pexman, 2021). The motor imagery data collected for this study were also reported in Dahm et al. (2022). After data cleaning there was an average of 152.1 participants per noun ($SD = 2.1$) and 84.0 nouns per participant ($SD = 0.9$) in the BOI SCT. In the foot/leg action strength SCT there was an average of 150.9 participants per verb ($SD = 2.8$) and 74.5 verbs per participant ($SD = 0.9$).

2.1.2. Materials

2.1.2.1. Syntactic classification tasks.
In the BOI SCT the sensorimotor effect was quantified as the difference in response time and/or accuracy between words high (e.g., hammock, pot) and low (e.g., rainbow, chord) in BOI ratings. We used the same target and distractor stimuli as in Muraki and Pexman (2021). The stimuli included 50 high BOI nouns and 50 low BOI nouns. Further, 100 verbs (e.g., clench, remove) were used as distractors. The nouns (high and low BOI) and verbs were matched on other lexical and semantic dimensions known to influence response time including word length (Balota et al., 2007), frequency (log subtitle frequency; Brysbaert & New, 2009), prevalence (matched for nouns only, the number of people who know a word; Brysbaert, Mandera, McCormick, & Keuleers, 2019), orthographic Levenshtein distance (OLD; the minimum number of letter substitutions, insertions or deletions to change one word to another; Yarkoni, Balota, & Yap, 2008), age of acquisition (the estimated age when a word is acquired; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012), imageability (the degree to which a word can arouse a mental image; Cortese & Fugett, 2004; Schock, Cortese, & Khanna, 2012) and concreteness (the degree to which you can experience what a word refers to through one of the five senses; Brysbaert, Warriner, & Kuperman, 2014).

In the foot/leg action strength SCT the sensorimotor effect was quantified as the difference in response time and/or accuracy between words either high (e.g., jog, peddle) or low (e.g., help, jab) in foot/leg action strength ratings. We selected stimuli using the foot/leg action strength ratings collected by Lynott et al. (2020). The final stimuli were 40 verbs with high foot/leg action ratings (indicating more foot-action meaning), 40 verbs with low foot/leg action ratings (indicating less foot-action meaning), and 80 nouns (e.g., lunch, story) that were used as

[1] Our full sample was retained to provide sufficient power to detect our effects of interest. The analysis scripts examining only first language English speakers (Experiment 1 $n = 107$) are available at https://osf.io/t3gys/. In summary, with a sample of only first language English speakers one significant interaction between motor imagery measures and sensorimotor effects changes when predicting BOI SCT accuracy, and it changes from involving one imagery subscale (FPIQ Kinesthetic) to another imagery subscale (FPIQ Action).

distractors. All stimuli (verbs and nouns) were matched on the same lexical and semantic variables as were the stimuli for the BOI SCT (word length, frequency, OLD, age of acquisition, imageability, concreteness), with the exception of prevalence.[2] We used an exact matching procedure implemented via the LexOPS R package (Taylor, Beith, & Sereno, 2020), which matches stimuli at a word level within each group (e.g., each high foot/leg action verb is matched on the specified variables to a corresponding low foot/leg action verb). None of the stimuli were in both stimuli sets. Please see the supplemental materials for detailed descriptive statistics (Supplementary Table 1) and lists of the word stimuli (Supplementary Tables 2 and 3).

2.1.2.2. Motor imagery measures

2.1.2.2.1. Florida Praxis Imagery Questionnaire. The FPIQ (Ochipa et al., 1997) has four subscales (kinesthetic, position, action, and object imagery) of twelve items each. Kinesthetic imagery describes the joints moving during an action (e.g., imagine you are using a pair of scissors. Which joint moves more, your wrist or your finger joints?). Position imagery describes the hand and body position in relation to other objects during an action (e.g., imagine you are using a carving knife. Does your palm face the ceiling or the floor?). Action imagery describes the motion of a limb during an action (e.g., imagine you are using a pair of scissors. Does your hand move towards or away from your body?). Object imagery describes a judgement about an object used during an action (e.g., is the blade of a carving knife wider where it meets the handle or at the tip?). Participants are asked to choose the correct response from two options. Subscale scores range from 0 to 12 which indicates the number of correct responses.

2.1.2.2.2. Mental body rotation task. For the MBRT (Dahm et al., 2022; Steggemann et al., 2011), 64 experimental images of a human figure were created, with half viewing a figure from the back and half from the front (see Fig. 1a & 1b). In each figure either the left or right arm or leg is extended. Each image was presented three times in three types of orientation (head up trials rotated 0°, 45°, 315°; head down trials rotated 135°, 180°, 225°; and head middle trials rotated 90°, 270°), for a total of 192 trials. The images were presented in random order on a white background. Participants indicated as fast and accurately as possible whether the left or right limb was extended. The response buttons were “k” for a right limb and “d” for a left limb. Upon response, the next stimulus was presented. Ahead of data collection, participants completed eight practice trials with feedback. After completing 96 trials, they were offered a break.

2.1.2.2.3. Test of ability in movement imagery. The TAMI (Madan & Singhal, 2013) consists of 10 questions. Each question provides five written instructions that describe the movement elements of one body part (e.g., step your foot 30 cm forward, raise your left arm forward to reach 90°, tilt your head down towards your chest). Participants are asked to imagine completing the series of five instructed movement elements. After the instruction of the last element, participants select one out of five visual stimuli which matches the final imagined body position, or alternatively select the response options “none” or “unclear”.

2.1.2.3. Control measures

2.1.2.3.1. Edinburgh handedness inventory. To account for potential response time differences on the MBRT due to handedness participants completed the Edinburgh Handedness Inventory (EHI; Oldfield, 1971), which quantifies the degree to which a person is left- or right-handed based on their preferred hand to use in a variety of daily activities (e.g., drawing or using scissors). Scores range between −100 (left-hand preference), 0 (no preference), and 100 (right-hand preference).

2.1.2.3.2. Vividness of movement imagery questionnaire 2. To account for the visual component of motor imagery (e.g., vividness of visual image, first- or third-person perspective) in any interactions we observed, participants completed a computer version of the Vividness of Movement Imagery Questionnaire 2 (VMIQ-2; Dahm, 2022; Roberts et al., 2008). The questionnaire involves imagining twelve actions and rating the imagery vividness of each action in external visual imagery (watching yourself perform a movement from an external view), internal visual imagery (looking through your own eyes while performing a movement), or kinesthetic imagery (feeling yourself do a movement) on a scale from 1 (perfectly clear) to 5 (no image at all).

2.1.3. Procedure

The study was administered through Qualtrics (https://www.qualtrics.com) and Pavlovia (https://www.pavlovia.com). The syntactic classification and mental body rotation tasks were programmed using the PsychoPy Builder interface (Peirce et al., 2019) and run online using PsychoJS Version 3.2 (Bridges, Pitiot, MacAskill, & Peirce, 2020). Participants completed two syntactic classification tasks. In the BOI task, participants responded only to nouns. In the foot/leg action strength task, they responded only to verbs. Before each task, participants completed 10 practice trials with feedback. In both tasks, the stimuli were presented in Arial font (letter height as a proportion of the participant’s screen was 0.025) in black letters on a white background. Each trial began with a blank screen (500 ms), followed by a fixation cross (500 ms) and then a single word was presented and remained on the screen for 3 s or until the participant made a response. Participants were asked to respond as quickly and accurately as possible if the word was a noun (in the BOI SCT) or, separately, a verb (in the foot/leg action strength SCT). If the word was not a noun or verb in each task respectively, participants were instructed to make no response and wait for the next word trial to begin. The response buttons were either “k” or “d” and were counterbalanced across the two tasks and across participants. After completing half the word stimuli (i.e., after 100 trials of the BOI SCT and after 80 trials of the foot/leg action strength SCT) participants were offered a break. The order of the two syntactic classification tasks was counterbalanced across participants and stimuli were presented in a different random order for each participant. After completing the two SCTs participants completed the MBRT. Thereafter, participants completed the EHI, FPIQ, TAMI, and VMIQ-2 (presented in random order to each participant).

2.1.4. Data cleaning and analysis

Data cleaning and analyses were conducted using the statistical software R (Version 4.2.1; R Core Team, 2022) and the following packages: apaTables (version 2.0.8; Stanley, 2021), emmeans (version 1.7.5; Lenth, 2022), lme4 (version 1.1.30; Bates, Kliegl, Vasishth, & Baayen, 2015; Bates, Mächler, Bolker, & Walker, 2015), lmerTest (version 3.1.3; Kuznetsova, Brockhoff, & Christensen, 2017), performance (version 0.9.1; Lüdecke, Ben-Shachar, Patil, Waggoner, & Makowski, 2021), tidyverse (version 1.3.2; Wickham et al., 2019), and sjPlot (version 2.8.10; Lüdecke, 2021). The data and analysis scripts can be found at https://osf.io/t3gys/. Data from inattentive participants were removed where accuracy rates were significantly lower than chance (50% using a binomial test) in either the BOI SCT ($n = 10$) or the foot/leg action strength SCT ($n = 7$). Data were also removed for participants with MBRT accuracy rates significantly lower than chance as this indicated that participants were simply clicking through the task without attending to it ($n = 16$). Further, participants’ data were excluded if their accuracy was <10% on front-view trials and >90% on back-view trials, indicating non-compliance with task instructions and adopting solely one perspective for the task ($n = 6$). Data from one additional participant were removed due to a response time on the MBRT that indicated they were interrupted during the task for over 40 min. Data for a further five participants were excluded from the analyses due to incomplete data in the questionnaires. In sum, 31 data for unique participants were excluded from the analyses, leaving data for a total of

[2] When prevalence is added as a covariate to the best fit models predicting response time and accuracy in the foot/leg action SCT the observed effects remained significant.

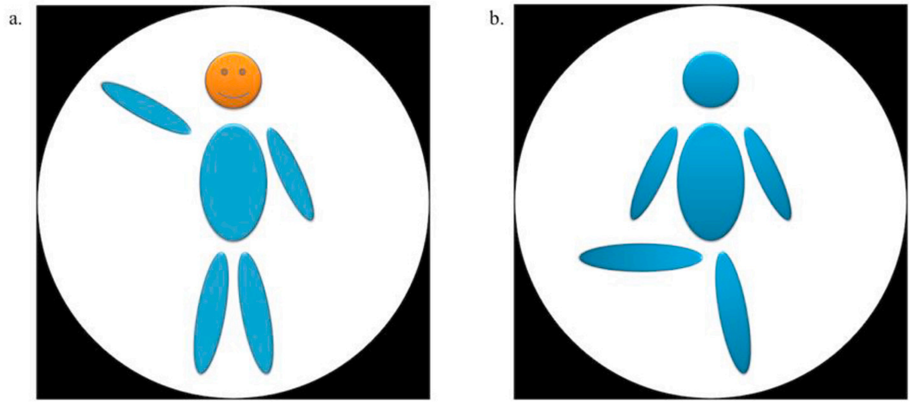

Fig. 1. Example Figures of MBRT with a) a front-view rotated at 0° having the right hand/arm extended and b) a back-view rotated at 0° having the left leg extended.

154 participants in the analyses.

Trial-level data from the SCTs were cleaned by first removing data for any word with significantly lower than chance accuracy from all participants' datasets. This resulted in the removal of data for 15 words (five high BOI, ten low BOI) from the BOI SCT and four words (one high foot/leg action strength, three low foot/leg action strength) from the foot/leg action strength SCT (see Supplementary Tables 2 and 3 for the specific words removed). As a final step of data cleaning, trials with response times that fell +/− 3 standard deviations from an individual participant's mean response time were excluded from each SCT. For full descriptive statistics on response times, accuracies and number of trials included/excluded see Supplementary Table 4.

Motor imagery abilities were quantified as total scores for the VMIQ-2, TAMI, and each FPIQ subscale, and composite linear speed-accuracy scores (LISAS) to account for speed-accuracy tradeoff in the MBRT data (Dahm et al., 2022). LISAS combine response time, accuracy, and consideration of their respective variances (Vandierendonck, 2017). In the case of high accuracy, LISA scores show little deviation from RT, but increase with a corresponding decrease in accuracy (Steggemann et al., 2011). We selected the LISA score for our statistical models that was the most sensitive to individual variability in imagery ability (front-view, head-down, foot/leg trials), consistent with previous evidence that body rotation tasks are more difficult from a front-view rather than back-view and are more difficult as the rotation angle increases (Dahm et al., 2022; Steggemann et al., 2011). Finally, we calculated a handedness quotient based on responses to the EHI (Oldfield, 1971).

We tested the hypotheses using linear mixed effects models to predict response time and logistic mixed effects models to predict the probability of an accurate response due to the binary nature of the dependent variable (e.g., correct/incorrect). Only go trials were included in the models because no response time data were collected for no-go trials. All continuous predictors were transformed to z-scores prior to entry in the models. In each model we entered EHI and VMIQ-2 scores to control for participant handedness and the visual component of motor imagery respectively. The data were inspected for non-normality and homogeneity of variance and we log-transformed response times to improve the normality of residuals and homogeneity of variance.

We used the parsimonious mixed models approach described by Bates, Kliegl, et al. (2015) to select the random effects structure for our models. In brief, a maximal model including all possible random intercepts and slopes was adopted as a starting point. In the event of non-convergence or a singular fit of the maximal model, the models were simplified first by removing correlations between random slopes and intercepts, and then removing random slopes beginning with higher order terms until the model converged. We then conducted a principal components analysis (PCA) on the random effects and removed components that explained <1% of the variance to develop the most parsimonious random effect structure. If correlations had been removed in a previous step, they were re-added at the final stage and tested to see if they improved the fit of the most parsimonious model. Once the random effect structure was determined, we tested the inclusion of interaction terms between item level and subject level fixed effects to identify the best overall model fit.

2.2. Results

The correlations between all motor imagery variables and response times on the BOI and foot/leg action strength SCTs are presented in Table 1. Descriptive statistics for the SCTs and MBRT (including mean response time and accuracy by trial type) are presented in the supplemental materials (Supplementary Table 4).

For the BOI SCT models we entered fixed effects of BOI (high coded as 1, low coded as 0), and the FPIQ subscale scores (see Table 2 for fixed effect model comparisons). The best fitting model for response time was: RT ~ BOI + EHI + VMIQ-2 + FPIQ A + BOI*FPIQ B + FPIQ C + FPIQ D + (1 + BOI|Participant) + (1 + FPIQ A + FPIQ B|Item). This model[3] (Table 3) revealed a significant effect of BOI on response times, indicating faster RTs to high BOI nouns ($M = 1060.6$ ms, $SD = 439.7$) than to low BOI nouns ($M = 1161.9$ ms, $SD = 486.5$). There was also a significant interaction between scores on the FPIQ Position subscale and BOI. The interaction was decomposed to determine how the difference in response times to high and low BOI nouns varied as a function of FPIQ Position subscale scores.

We extracted estimated marginal means for five different levels of FPIQ Position z-score (ranging in 1-unit increments from −3.17 to 1.06, to capture the full range of values in the observed data). All pairwise contrasts were compared against a Bonferroni corrected alpha of 0.008. FPIQ Position z-scores that fell below zero (−3.17, −2.33, −1.48, and −0.63 indicating poorer imagery) showed no significant difference between high and low BOI noun response times ($b = -0.01$, $z = -0.70$, $p = .485$; $b = -0.02$, $z = -1.32$ $p = .188$; $b = -0.03$, $z = -1.98$, $p = .048$, and $b = -0.04$, $z = -2.59$, $p = .010$ respectively). In contrast, FPIQ position z-scores of 0.21 and 1.06 (indicating better imagery) showed a significant difference between high and low BOI noun response times ($b = -0.04$, $z = -3.05$, $p = .002$ and $b = -0.05$, $z = -3.34$, $p < .001$ respectively; see Fig. 2).

The best fitting model for accuracy was: Acc ~ BOI + EHI + VMIQ-2 + BOI*FPIQ A + FPIQ B + FPIQ C + FPIQ D + (1 + BOI||Participant) +

[3] Although we matched our BOI SCT stimuli on important lexical semantic variables such as word frequency, length, and concreteness, we did not use the same exact matching procedure as used for the other three SCTs. Therefore, we conducted additional analyses adding these control variables as covariates to the best fit models for response time and accuracy in this task. The inclusion of these covariates did not change the significant effects reported here.

Table 1
Participant means, standard deviations, and correlations on motor imagery measures and syntactic classification task response times and accuracies in experiment 1.

Variable	*M*	*SD*	1	2	3	4	5	6	7	8	9	10	11
1. EHI Quotient	74.6	34.3											
2. FPIQ Kinesthetic	9.6	1.4	0.07										
3. FPIQ Position	10.8	1.2	0.12	0.01									
4. FPIQ Action	10.9	1.4	0.13	**0.21***	**0.28***								
5. FPIQ Object	11.1	1.0	0.06	**0.20***	**0.22***	**0.34***							
6. MBRT LISAS	2823.1	1436.2	0.11	0.05	−0.02	0.11	−0.06						
7. TAMI	13.9	5.2	0.04	**0.21***	**0.26***	**0.23***	**0.20***	0.03					
8. VMIQ-2	73.9	25.8	0.01	−0.02	−0.02	0.06	0.13	0.11	0.02				
9. BOI SCT RT (ms)	1115.8	200.7	0.06	0.03	0.03	0.03	0.02	**0.16***	0.01	0.05			
10. BOI SCT Acc (%)	91.1	9.0	−0.07	0.07	−0.02	0.02	0.13	−0.07	0.04	0.06	**−0.46***		
11. Foot/Leg SCT RT (ms)	920.0	184.4	−0.02	0.01	0.15	**0.23***	−0.05	**0.23***	−0.02	0.02	**0.64***	**−0.32***	
12. Foot/Leg SCT Acc (%)	92.8	6.0	−0.12	**0.29***	−0.03	0.01	**0.18***	**−0.18***	0.07	0.09	**−0.30***	**−0.45***	**−0.45***

Note. EHI = Edinburgh Handedness Inventory; FPIQ = Florida Praxis Imagery Questionnaire; MBRT LISAS = linear speed accuracy score for front-view, upside-down leg trials of the Mental Body Rotation Task; TAMI = Test of Ability in Movement Imagery; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; SCT = Syntactic Classification Task; RT = Response Time; Acc = Accuracy; Foot/Leg = Foot/Leg Action Strength.
* $p < .05$ uncorrected.

Table 2
Model comparisons for BOI SCT fixed effect interactions using likelihood ratio tests.

Model	Interaction	Compared Model	*AIC*	*BIC*	*log likelihood*	χ^2	*df*	*p*
Response Time Models								
1	NA		176,668	176,779	−88,319			
2	BOI x EHI	1	176,669	176,787	−88,319	1.17	1	0.279
3	BOI x VMIQ-2	1	176,669	176,787	−88,319	1.08	1	0.299
4	BOI x FPIQ Kin	1	176,669	176,787	−88,318	1.57	1	0.210
5	BOI x FPIQ Position	1	176,662	176,780	−88,315	8.23	1	0.004*
6	BOI x FPIQ Position BOI x FPIQ Action	5	176,662	176,788	−88,314	1.49	1	0.222
7	BOI x FPIQ Position BOI x FPIQ Object	5	176,661	176,787	−88,314	2.62	1	0.105
Accuracy Models								
1	NA		5685.6	5782.7	−2829.8			
2	BOI x EHI	1	5687.2	5791.7	−2829.6	0.40	1	0.529
3	BOI x VMIQ-2	1	5686.3	5790.9	−2829.2	1.27	1	0.260
4	BOI x FPIQ Kin	1	5682.1	2756.7	−2827.1	5.45	1	0.020*
5	BOI x FPIQ Kin BOI x FPIQ Position	4	5683.3	5795.3	−2826.7	0.80	1	0.370
6	BOI x FPIQ Kin BOI x FPIQ Action	4	5681.1	5793.1	−2825.6	3.00	1	0.083
7	BOI x FPIQ Kin BOI x FPIQ Object	4	5684.0	5796.0	−2827.0	0.17	1	0.677

Note. AIC= Akaike information criterion; BIC = Bayesian information criterion; BOI = Body-object interaction; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; FPIQ = Florida Praxis Imagery Questionnaire; KIN = Kinesthetic. All models included fixed effects of BOI, EHI, VMIQ-2, and all FPIQ subscales. Models 2–7 include the respective interaction listed in the column “interaction”. * $p < .05$ uncorrected.

(1 + FPIQ A + FPIQ D||Item). This model (Table 3) revealed a significant effect of BOI on accuracy (correct coded as 1, incorrect coded as 0). Correct responses were just over 2 times as likely for high BOI nouns than low BOI nouns. Furthermore, there was a significant interaction between BOI and FPIQ Kinesthetic scores. We extracted estimated marginal means for eight different levels of FPIQ Kinesthetic z-score (ranging in 1-unit increments from −3.36 to 1.81, to capture the full range of values in the observed data). All pairwise contrasts were compared against a Bonferroni corrected alpha of 0.006. FPIQ Kinesthetic z-scores that fell below 0 (−3.36, −2.63, −1.89, −1.15, and −0.41 indicating poorer imagery) showed no significant difference between high and low BOI noun accuracy ($OR = 1.03$, $z = 0.07$, $p = .945$; $OR = 1.22$, $z = 0.56$, $p = .575$; $OR = 1.45$, $z = 1.20$, $p = .231$; $OR = 1.72$, $z = 1.96$, $p = .050$; and $OR = 2.05$, $z = 2.76$, $p = .006$, respectively). In contrast, FPIQ Kinesthetic z-scores of 0.33, 1.07, and 1.81 (indicating better imagery) showed a significant difference between high and low BOI noun accuracy ($OR = 2.43$, $z = 3.41$, $p = .001$; $OR = 2.89$, $z = 3.79$, $p < .001$; and $OR = 3.44$, $z = 3.93$, $p < .001$ respectively; see Fig. 3).

For the foot/leg action strength SCT models, we entered fixed effects of foot action strength rating (high, low), TAMI scores, and MBRT LISA scores for front-view, upside-down leg trials (see Table 4 for fixed effect model comparisons). The best fitting model for response time was: RT ∼ Foot/leg Action + EHI + VMIQ-2 + TAMI + LISA + (1|Participant) + (1 + EHI + TAMI + LISA||Item). This model (Table 5) revealed a significant effect of foot/leg action strength ratings on SCT response times, indicating faster SCT responses to verbs with high foot/leg action strength ratings ($M = 890$ ms, $SD = 369.2$) compared to verbs with low foot/leg action strength ratings ($M = 941.9$ ms, $SD = 392.4$). There was also a significant simple effect of MBRT LISA score, such that people with higher LISA scores (indicating longer response times on front-view, upside-down leg trials) responded more slowly in the foot/leg action strength SCT. There were no significant interactions between foot/leg action strength ratings and the motor imagery measures.

The best fitting model for accuracy was: Acc ∼ Foot/leg Action + EHI + VMIQ-2 + TAMI + LISA + (1 + Foot/leg Action ||Participant) + (1 + EHI||Item). This model (Table 5) revealed a significant effect of foot/leg action strength ratings on accuracy, wherein responses to verbs with high foot/leg action strength ratings were just over 2 times as likely to be accurate compared to verbs with low foot/leg action strength ratings. There was also a significant effect of MBRT LISA score, such that for each unit increase in LISA scores (indicating longer response times) participants were 0.80 times as likely to respond accurately. There were

Table 3
Mixed effects models predicting BOI effects on SCT response times and accuracy.

	Linear Regression - Response Times			Logistic Regression - Accuracy		
Fixed Effects	*b*	95% *CI*	*p*	*OR*	95% *CI*	*p*
Intercept	3.04	[3.02, 3.07]	<0.001*	22.91	[15.09, 34.79]	<0.001*
BOI	−0.04	[−0.07, −0.01]	0.004*	2.25	[1.36, 3.73]	0.002*
EHI	0.00	[−0.01, 0.02]	0.585	0.84	[0.66, 1.06]	0.148
VMIQ-2	0.00	[−0.01, 0.02]	0.628	1.01	[0.81, 1.26]	0.922
FPIQ Kin	0.00	[−0.01, 0.02]	0.738	0.97	[0.76, 1.24]	0.832
FPIQ Position	0.01	[−0.01, 0.02]	0.247	0.91	[0.72, 1.16]	0.456
FPIQ Action	0.00	[−0.01, 0.02]	0.810	0.95	[0.74, 1.21]	0.672
FPIQ Object	−0.00	[−0.01, 0.01]	0.860	1.19	[0.94, 1.51]	0.156
BOI*FPIQ Kin	–	–	–	1.26	[1.05, 1.52]	0.014*
BOI*FPIQ Position	−0.01	[−0.02, −0.00]	0.009*	–	–	–
Random Effects	Variance	*SD*	*r*	Variance	*SD*	
Participant intercept	0.01	0.08		1.56	1.25	
BOI slope	0.00	0.03	−0.42	0.11	0.33	
Item Intercept	0.00	0.06		1.21	1.10	
FPIQ A slope	0.00	0.01	0.04	0.06	0.24	
FPIQ B slope	0.00	0.01	0.55	–	–	
FPIQ D slope	–	–	–	0.02	0.13	
Residual	0.02	0.13		3.29		
Model Fit	Marginal	Conditional		Marginal	Conditional	
R^2	0.017	0.375		0.040	0.479	

Note. CI = confidence interval; *OR* = odds ratio; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; FPIQ = Florida Praxis Imagery Questionnaire; Kin = Kinesthetic; *SD* = standard deviation. Word type is a binary variable with low BOI nouns as the reference group (0) and high BOI nouns as the focus group (1). Accuracy is a binary dependent variable with inaccurate responses as the reference group (0) and accurate responses as the focus group (1). The marginal R^2 includes only the variance from the fixed effects and the conditional R^2 includes variance from both the fixed and random effects. The model equation for response time was: RT ~ BOI + EHI + VMIQ-2 + FPIQ A + BOI*FPIQ B + FPIQ C + FPIQ D + (1 + BOI|Participant) + (1 + FPIQ A + FPIQ B|Item). The model equation for accuracy was: Acc ~ BOI + EHI + VMIQ-2 + BOI*FPIQ A + FPIQ B + FPIQ C + FPIQ D + (1 + BOI||Participant) + (1 + FPIQ A + FPIQ D||Item). *p*-values for fixed effects in the linear mixed effects model are calculated using Satterthwaite's method. *N* participants = 154, *N* words = 85. * *p* < .05 uncorrected.

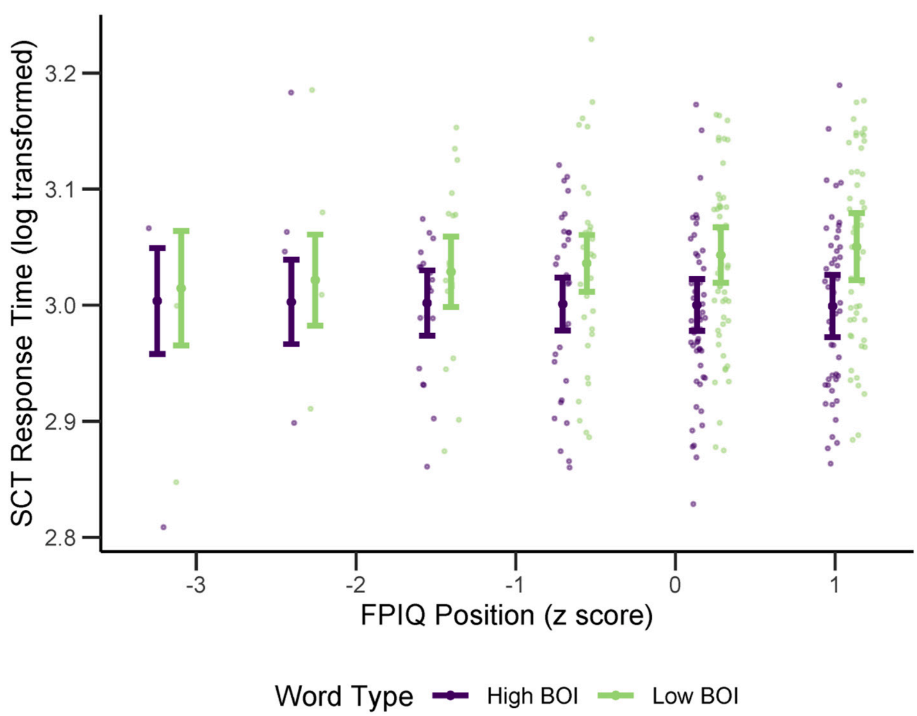

Fig. 2. Motor Imagery and BOI interaction effects on SCT response times derived from estimated marginal means for high and low BOI nouns. Error bars represent 95% confidence intervals. Points represent observed participant mean response times for high and low BOI nouns. SCT = Syntactic Classification Task; FPIQ = Florida Praxis Imagery Questionnaire; BOI = Body Object Interaction.

no significant interactions between foot/leg action strength ratings and the motor imagery measures.

2.3. *Experiment 1 discussion*

In Experiment 1, we replicated the previously observed interaction between scores on the FPIQ position subscale and BOI effects in syntactic classification task response times (Muraki & Pexman, 2021). The results suggest that BOI effects are only observed with average to high hand position motor imagery ability. Furthermore, we tested the relationship between BOI effects and motor imagery on response accuracy, to extend the findings previously reported in Muraki and Pexman (2021). We

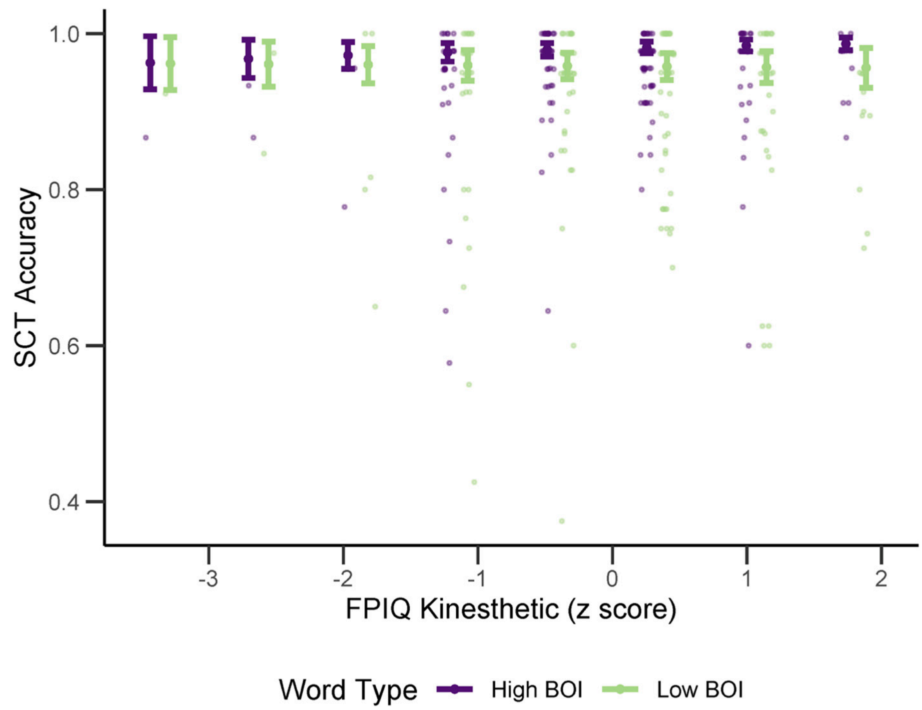

Fig. 3. Motor Imagery and BOI interaction effects on SCT accuracy derived from estimated marginal means for high and low BOI nouns. Error bars represent 95% confidence intervals. Points represent observed participant mean accuracy for high and low BOI nouns. SCT = Syntactic Classification Task; FPIQ = Florida Praxis Imagery Questionnaire; BOI = Body Object Interaction.

Table 4
Model comparisons for foot/leg action strength SCT fixed effect interactions using likelihood ratio tests.

Model	Interaction	Compared Model	*AIC*	*BIC*	*log likelihood*	χ^2	*df*	*p*
Response Time Models								
1	NA		157,452	157,540	−78,714			
2	Foot/leg action x EHI	1	157,452	157,546	−78,713	2.72	1	0.099
3	Foot/leg action x VMIQ-2	1	157,454	157,549	−78,714	0.15	1	0.700
4	Foot/leg action x TAMI	1	157,454	157,549	−78,714	0.06	1	0.814
5	Foot/leg action x MBRT LISAS	1	157,453	157,548	−78,714	0.78	1	0.378
Accuracy Models								
1	NA		3949.4	4022.9	−1964.7			
2	Foot/leg action x EHI	1	3950.1	4030.9	−1964.0	1.34	1	0.247
3	Foot/leg action x VMIQ-2	1	3951.3	4032.1	−1964.7	0.11	1	0.744
4	Foot/leg action x TAMI	1	3951.4	4032.2	−1964.7	0.01	1	0.935
5	Foot/leg action x MBRT LISAS	1	3950.1	4031.0	−1964.1	1.27	1	0.259

Note. AIC= Akaike information criterion; *BIC* = Bayesian information criterion; Foot/leg action = Foot/leg action strength rating (high or low); EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; TAMI = Test of Ability in Movement Imagery; MBRT LISAS = linear speed accuracy score for front-view, upside-down leg trials of the Mental Body Rotation Task. All models included fixed effects of foot/leg action strength, EHI, VMIQ-2, TAMI, and MBRT LISAS. Models 2–5 include the respective interaction listed in the column "interaction".

observed a relationship between the FPIQ Kinesthetic subscale and BOI effects on response accuracy, with better kinesthetic motor imagery scores related to less accurate responses to low BOI words. This FPIQ subscale measures imagery of joint movement during object-directed actions related to the hand, wrist, and arm.

We also investigated the sensorimotor effect of foot/leg action strength ratings on verb processing. We found an effect of foot/leg action strength rating on response times, where words with higher foot/leg action strength ratings were processed more quickly than those with lower foot/leg action strength ratings, suggesting these words benefit from sensorimotor simulation of foot/leg movements during semantic processing. We also observed an effect of MBRT LISA scores on response times, where participants with slower responses on the MBRT also had slower responses in the SCT. This is consistent with findings that processing speed is associated with both domain-general and domain-specific processes (Hintz et al., 2020) and thus similarity in processing speed at a participant-level can be observed across different types of cognitive tasks. Standardized response times are often used in language processing studies to remove the influence of participant processing speed (Yap, Balota, Sibley, & Ratcliff, 2012) and to control for individual differences in processing speed across tasks (Ratcliff, Thapar, & McKoon, 2010).

We did not, however, find a relationship between foot imagery ability and foot/leg action strength effects in the foot/leg action strength SCT. The lack of interaction between MBRT LISA scores and foot/leg action strength effects in the SCT suggests that sensorimotor simulation of foot/leg information does not share mechanisms with motor imagery, which is inconsistent with the findings for hand information from the BOI SCT. One explanation for these inconsistent findings is that the mechanisms supporting imagery and simulation of skilled, object-directed actions like those captured in BOI differ from the mechanisms supporting imagery and simulation of more general motor experience,

Table 5
Mixed effects models predicting foot/leg action strength effects on SCT response times and accuracy.

	Linear Regression - Response Times			Logistic Regression - Accuracy		
Fixed Effects	*b*	95% *CI*	*p*	*OR*	95% *CI*	*p*
Intercept	2.95	[2.93, 2.96]	<0.001*	36.26	[23.97, 54.85]	< 0.001*
Foot/leg action	−0.03	[−0.04, −0.01]	0.001*	2.11	[1.24, 3.60]	0.006*
EHI	−0.00	[−0.02, 0.01]	0.605	0.85	[0.67, 1.09]	0.195
VMIQ-2	0.00	[−0.01, 0.01]	0.887	1.16	[0.93, 1.44]	0.197
TAMI	−0.00	[−0.01, 0.01]	0.809	1.12	[0.90, 1.39]	0.319
MBRT LISAS	0.02	[0.01, 0.03]	0.005*	0.80	[0.65, 0.99]	0.037*
Random Effects	Variance	*SD*		Variance	*SD*	
Participant Intercept	0.01	0.08		1.28	1.13	
Foot/leg action slope	–	–		0.58	0.76	
Item Intercept	0.00	0.03		0.96	0.98	
EHI slope	0.00	0.01		0.02	0.13	
TAMI slope	0.00	0.00		–	–	
MBRT LISAS slope	0.00	0.01		–	–	
Residual	0.02			3.29		
Model Fit	Marginal	Conditional		Marginal	Conditional	
R^2	0.020	0.299		0.043	0.431	

Note. CI = confidence interval; *OR* = odds ratio; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; TAMI = Test of Ability in Movement Imagery; MBRT LISAS = linear speed accuracy score for front-view, upside-down leg trials of the Mental Body Rotation Task; *SD* = standard deviation. Word type is a binary variable with verbs with low foot/leg action strength ratings as the reference group (0) and verbs with high foot/leg action strength ratings as the focus group (1). Accuracy is a binary dependent variable with inaccurate responses as the reference group (0) and accurate responses as the focus group (1). The marginal R^2 includes only the variance from the fixed effects and the conditional R^2 includes variance from both the fixed and random effects. The model equation for response time was: RT ~ Foot/leg Action + EHI + VMIQ-2 + TAMI + LISA + (1|Participant) + (1 + EHI + TAMI + LISA||Item). The model equation for accuracy was: Acc ~ Foot/leg Action + EHI + VMIQ-2 + TAMI + LISA + (1 + Foot/leg Action ||Participant) + (1 + EHI||Item). *p*-values for fixed effects in the linear mixed effects model are calculated using Satterthwaite's method. *N* participants = 154, *N* words = 76. * *p* < .05 uncorrected.

like that captured in the foot/leg action strength ratings. Therefore, we may observe interactions between BOI effects and the FPIQ because the sensorimotor simulation involves not only effector movement, but specifically hands interacting with objects. In addition, we may not observe interactions between foot motor imagery and foot/leg action sensorimotor effects because we do not typically use our feet for fine motor movements, as we do with hands. Therefore, the effects we observed in the BOI and FPIQ replication may be the result of hand movements requiring more fine-grained skill and thus may be based in an object-directed action representation system that is also used during sensorimotor processing. In Experiment 2, we tested this proposal by examining whether hand movement imagery interacts with hand/arm action strength effects in semantic processing.

3. Experiment 2

In Experiment 2, we investigated whether the object-directed nature of BOI was an important factor in the interaction first observed in Muraki and Pexman (2021) and subsequently replicated in Experiment 1. There is some evidence to suggest that object-directed actions may be distinct from other hand actions. For instance, object-based representations are associated with activity in the canonical neuron system, whereas actions in the absence of objects are associated with activity in the mirror neuron system (Oztop & Arbib, 2002). Therefore, we tested whether the ability to imagine hand actions is associated with processing hand/arm-related action verbs. Finally, we tested whether whole body motor imagery ability is associated with the relative embodiment effect that has previously been reported for verb stimuli (Sidhu et al., 2014; Sidhu & Pexman, 2016). This research question affords the opportunity to further test generalization of correlations observed between imagery ability and sensorimotor effects, and whether consistency between the type of motor imagery being measured (in this case whole-body motor imagery) and the form of sensorimotor simulation captured by the chosen semantic dimension (embodiment, involving general actions of the human body) is necessary to observe individual differences in sensorimotor effects in language processing.

If the interaction between motor imagery and sensorimotor effects in semantic processing is specific to object-directed actions, we expected to find no relationship between hand motor imagery ability and hand/arm action strength effects in response time and accuracy, because hand action does not necessarily involve objects. However, if the interaction between motor imagery and sensorimotor effects in semantic processing is specific to hands due to their unique dexterity and ability for fine-motor movements, we would expect to find a relationship between hand motor imagery ability and hand/arm action strength effects. To further test the nature of shared mechanisms between motor imagery and sensorimotor simulation, we expanded from the manipulations related to hand/arm and foot/leg meaning to investigate whether whole-body imagery is related to processing word meaning that is related to the entire body.

3.1. Method

3.1.1. Participants

One hundred and ninety-five participants (148 female, 40 male, 2 non-binary, 5 did not respond, *M* age = 20 years, *SD* = 3.3) completed this online study in exchange for psychology course credit at the University of Calgary. Of the sample, 157 were retained following our data cleaning procedures (118 female, 33 male, 2 non-binary, 4 did not respond, *M* age = 20 years, *SD* = 3.5). Of the retained sample, 113 reported that English was their first language.[4] Those reporting that English was not their first language reported being either completely fluent (*n* = 22), very fluent (*n* = 10), or somewhat fluent (*n* = 2). One participant reported being not fluent, so their data were removed from the analysis. We based our target sample size on the same criteria as in Experiment 1. After data cleaning there was an average of 154.2 participants per verb (*SD* = 2.7) and 91.3 verbs per participant (*SD* = 1.0) in the hand/arm action strength SCT. In the embodiment SCT there was an average of 154.7 participants per verb (*SD* = 1.4) and 93.6 verbs per participant (*SD* = 1.2).

[4] Once again, our full sample was retained to provide sufficient power to detect our effects of interest. The analysis scripts examining only first language English speakers (Experiment 2 *n* = 113) are available at https://osf.io/t3gys/. In summary, there is also one sensorimotor simple effect that is observed in the first language English speakers only analysis but not observed in the analyses reported in Experiment 2 (an embodiment accuracy effect).

3.1.2. Materials

3.1.2.1. Syntactic classification tasks. In the hand/arm strength SCT the sensorimotor effect was quantified as the difference in response time and/or accuracy between words either high (e.g., applaud, pluck) or low (e.g., arrive, explode) in hand/arm action strength ratings. We selected stimuli using the hand/arm action strength ratings collected by Lynott et al. (2020). The final stimuli were 50 verbs with high hand/arm action ratings (indicating more hand-action meaning), 50 verbs with low hand/arm action strength ratings (indicating less hand-action meaning) and 100 nouns that were used as filler stimuli. All stimuli (verbs and nouns) were matched on the lexical and semantic dimensions of word length (Balota et al., 2007), frequency (Brysbaert & New, 2009), orthographic Levenshtein distance (Yarkoni et al., 2008), age of acquisition (Kuperman et al., 2012), imageability (Cortese & Fugett, 2004; Schock et al., 2012) and concreteness (Brysbaert et al., 2014).[5]

In the embodiment SCT the sensorimotor effect was quantified as the difference in response time and/or accuracy between words either high or low in embodiment ratings. We selected stimuli using the embodiment ratings collected by Sidhu et al. (2014; the extent to which verbs refer to actions, states or relations that easily involve the human body). The final stimuli were 50 verbs with high embodiment ratings, 50 verbs with low embodiment ratings, and 100 nouns that were used as filler stimuli for the task. All stimuli (verbs and nouns) were matched on the same lexical and semantic dimensions as the other stimuli in Experiment 2, except for imageability, which was not matched due to the low availability of imageability norms for the verbs with embodiment ratings. Exact matching for stimuli in both tasks was performed using the LexOPS package (Taylor et al., 2020), as described in Experiment 1. None of the stimuli were in both stimuli sets. Please see the supplemental materials for detailed descriptive statistics (Supplementary Table 5) and lists of the word stimuli (Supplementary Tables 6 and 7).

3.1.2.2. Motor imagery and control measures. We used the same motor imagery (MBRT, Dahm, 2020; Dahm et al., 2022; TAMI, Madan & Singhal, 2012; FPIQ, Ochipa et al., 1997) and control measures (EHI, Oldfield, 1971; VMIQ-2, Roberts et al., 2008) as Experiment 1. In addition, we included a Hand Laterality Judgement Task (HLJT; Parsons, 1987) as an additional motor imagery task.

3.1.2.2.1. Hand laterality judgement task. For the HLJT, 32 experimental images of a human hand were created, with half showing the hand with the palm down and half showing it with the palm up (see Fig. 4a & 4b). Each image was presented three times in three types of orientation (fingers up trials rotated 0°, 45°, 315°; fingers down trials rotated 135°, 180°, 225°; and fingers middle trials rotated 90°, 270°), for a total of 96 trials. The images were presented in a different random order for each participant on a white background. Participants indicated as quickly and accurately as possible whether the image showed a left or right hand. The response buttons were "k" for a right hand and "d" for a left hand. Ahead of data collection, participants completed eight practice trials with feedback.

Fig. 4. a) An example of an HLJT palm-down, fingers-up right-hand image. b) An example of an HLJT palm-up, fingers-down right-hand image. HLJT = hand laterality judgement task.

3.1.3. Procedure

The study was administered through Qualtrics (https://www.qualtrics.com) and Pavlovia (https://www.pavlovia.com). The SCTs and MBRT were programmed using the PsychoPy Builder interface (Peirce et al., 2019) and presented online using PsychoJS Version 2021.1.0 (Bridges et al., 2020). Participants completed two SCTs, in which they were instructed to respond only to verbs. The SCTs used the same procedure (e.g., timing, format of word presentation) as Experiment 1. The order of the two SCTs was counterbalanced across participants and stimuli were presented in a different random order for each participant. After completing the two SCTs participants completed the HLJT and the MBRT (in that order). Thereafter, participants completed the EHI, FPIQ, TAMI, and VMIQ-2 (presented in a random order to each participant).

3.1.4. Data cleaning and analysis

Data cleaning and analyses were conducted using the statistical software R (Version 4.2.1; R Core Team, 2022) using the same packages as Experiment 1. The data and analysis scripts can be found at https://osf.io/t3gys/. Data from inattentive participants were removed where accuracy rates were significantly lower than chance in either the hand/arm action strength SCT ($n = 10$) or the embodiment SCT ($n = 18$). Data were also removed for participants with HLJT and MBRT accuracy rates significantly lower than chance as this indicated that participants were simply clicking through the task without attending to it ($n = 10$ and $n = 17$ respectively). Further, participants' data were excluded if their accuracy was <10% on front-view trials and >90% on back-view trials, indicating non-compliance with task instructions and adopting solely one perspective for the task ($n = 1$ for the MBRT). Data for a further 11 participants were excluded due to incomplete data in the questionnaires. In sum, 38 data for unique participants were excluded from the analyses, leaving data for a total of 157 participants in the analyses.

Trial-level data from the SCTs were cleaned by first removing data for any word with significantly lower than chance accuracy from all participants' datasets. This resulted in the removal of seven words (one with high hand/arm action strength ratings, six with low hand/arm action strength ratings) from the hand/arm action strength SCT and five words (all with low embodiment ratings) from the embodiment SCT (see Supplementary Tables 6 and 7 for the specific words removed). As a final step of data cleaning, trials with response times that fell +/− 3 standard deviations from an individual participant's mean were excluded in the SCTs. For full descriptive statistics on response times, accuracies and number of trials included/excluded please see Supplementary Table 8.

Motor imagery abilities were quantified as total scores for the VMIQ-2, TAMI, and each FPIQ subscale, and composite linear speed-accuracy scores (LISAS) for the most difficult trials in the HLJT and the MBRT to increase our sensitivity to individual differences in motor imagery (e.g., from the palm-up and fingers-down trials in the HLJT and the front-view, head-down, leg trials of the MBRT). Finally, we calculated a handedness quotient based on responses to the EHI (Oldfield, 1971). We used the same procedures as described in Experiment 1 for our statistical models, including how random effect structures were selected and how the inclusion of interaction terms in the models predicting SCT response time and accuracy were tested.

3.2. Results

Correlations between all motor imagery variables and response times on the SCTs are presented in Table 6. Descriptive statistics for the SCTs, HJLT, and MBRT (including mean response time and accuracy by trial

[5] Prevalence not matched in the hand/arm action strength SCT or embodiment SCT stimuli. When it was added as a covariate to the best fit models predicting response time and accuracy for each SCT and the observed effects remained significant.

Table 6
Participant means, standard deviations, and correlations on motor imagery measures and syntactic classification task response times and accuracies in experiment 2.

Variable	*M*	*SD*	1	2	3	4	5	6	7	8	9	10	11	12
1. EHI Quotient	72.27	41.95												
2. FPIQ Kinesthetic	9.46	1.39	−0.08											
3. FPIQ Position	10.36	1.38	0.04	**0.20***										
4. FPIQ Action	10.82	1.54	0.01	**0.32***	**0.44***									
5. FPIQ Object	10.96	1.43	0.01	**0.29***	**0.47***	**0.58***								
6. HLJT LISA	2048.52	794.38	0.04	−0.06	−0.13	−0.00	0.02							
7. MBRT LISA	2313.19	1485.73	−0.04	0.04	−0.01	−0.02	0.06	**0.42***						
8. TAMI	13.88	4.99	−0.09	**0.18***	**0.35***	**0.36***	**0.23***	−0.08	**−0.16***					
9. VMIQ-2	66.52	28.72	0.01	−0.05	−0.04	−0.16	−0.06	0.13	**0.19***	**−0.17***				
10. Hand/arm Action SCT RT (ms)	974.75	171.02	0.01	0.00	−0.15	−0.06	−0.13	0.13	0.05	−0.06	−0.11			
11. Hand/arm Action SCT Acc (%)	90.22	4.90	−0.05	0.09	**0.20***	**0.18***	**0.17***	−0.06	0.05	**0.24***	0.09	**−0.48***		
12. Embodiment SCT RT (ms)	1102.43	202.53	−0.10	0.02	−0.01	−0.05	−0.04	0.11	0.09	0.04	0.00	**0.70***	**−0.22***	
13. Embodiment SCT Acc (%)	85.36	6.44	0.02	**0.21***	**0.17***	**0.21***	0.11	−0.10	−0.07	**0.18***	0.11	**−0.33***	**0.58***	**−0.38***

Note. EHI = Edinburgh Handedness Inventory; FPIQ = Florida Praxis Imagery Questionnaire; HLJT LISAS = linear speed accuracy score for palm-up, fingers-down trials of the Hand Laterality Judgement Task; MBRT LISAS = linear speed accuracy scores for front-view, upside-down leg trials of the Mental Body Rotation Task; TAMI = Test of Ability in Movement Imagery; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; SCT = Syntactic Classification Task; RT = Response Time; Acc = Accuracy. * $p < .05$ uncorrected.

type) are presented in the supplemental materials (Supplementary Table 8).

For the hand/arm strength SCT models we entered fixed effects of hand/arm strength rating (high coded as 1, low coded as 0), the FPIQ subscale scores, and HLJT LISAS for palm-up, fingers-down trials (see Table 7 for fixed effect model comparisons). The best fitting model for response time was: RT ~ Hand/Arm Action + EHI + VMIQ-2 + FPIQ A + FPIQ B + FPIQ C + FPIQ D + Hand/Arm Action*HLJT LISAS + (1 + Hand/Arm Action|Participant) + (1 + FPIQ D|Item). This model (Table 7) revealed a significant effect of hand/arm actions strength rating on response times, indicating faster responses to verbs with high hand/arm action strength ratings ($M = 903.6$ ms, $SD = 372.7$) compared to verbs with low hand/arm action strength ratings ($M = 977.8$ ms, $SD = 423.6$). We also observed significant effect of HLJT LISA scores on response times, indicating that participants who provided slower responses on the most difficult HJLT trials also provided slower responses on the SCT. Finally, we observed a significant interaction between HLJT LISA scores and hand/arm action strength. The interaction was decomposed and probed to determine how the difference in response times to verbs with high and low hand/arm action strength ratings varied as a function of HLJT LISA score.

We extracted estimated marginal means for six different levels of HLJT LISA score (ranging in 1-unit increments from −2 to 3, to capture the full range of values in the observed data). All pairwise contrasts were compared against a Bonferroni corrected alpha of 0.008. There was no significant difference between verbs high and low in hand/arm action strength ratings for HJLT LISA scores of −2 (i.e., the faster responses on HJLT palm-up, fingers-down trials; $b = -0.02$, $z = -2.02$, $p = .044$). In contrast, HLJT LISA scores of −1 and above (indicating slower responses on the palm-up, fingers-down trials) showed a significant difference between verbs high and low in hand/arm action strength ratings ($b = -0.03$, $z = -2.95$, $p = .003$, $b = -0.03$, $z = -3.79$, $p < .001$, $b = -0.04$, $z = -4.26$, $p < .001$, $b = -0.04$, $z = -4.33$, $p < .001$, and $b = -0.05$, $z = -4.20$, $p < .001$ respectively; see Fig. 5).

The best fitting model for accuracy was: Acc ~ Hand/Arm Action + EHI + VMIQ-2 + FPIQ A + FPIQ B + FPIQ C + FPIQ D + HLJT LISA + (1 + Hand/Arm Action||Participant) + (1 + EHI + FPIQ A + FPIQ D|| Item). This model (Table 8) revealed a significant effect of hand/arm

Table 7
Model comparisons for hand/arm action strength SCT fixed effect interactions using likelihood ratio tests.

Model	Interaction	Compared Model	*AIC*	*BIC*	*log likelihood*	χ^2	*df*	*p*
Response Time Models								
1	NA		192,465	192,584	−96,216			
2	Hand/Arm x EHI	1	192,467	192,594	−96,216	0.03	1	0.857
3	Hand/Arm x VMIQ-2	1	192,467	192,594	−96,216	0.05	1	0.824
4	Hand/Arm x FPIQ Kin	1	192,466	192,593	−96,216	0.70	1	0.403
5	Hand/Arm x FPIQ Position	1	192,466	192,594	−96,216	0.21	1	0.643
6	Hand/Arm x FPIQ Action	1	192,467	192,594	−96,216	0.09	1	0.764
7	Hand/Arm x FPIQ Object	1	192,465	192,592	−96,215	1.73	1	0.188
8	Hand/Arm x HLJT LISAS	1	192,463	192,590	−96,214	4.12	1	0.042*
Accuracy Models								
1	NA		6431.3	6544.9	−3200.7			
2	Hand/Arm x EHI	1	6433.2	6554.3	−3200.6	0.15	1	0.703
3	Hand/Arm x VMIQ-2	1	6431.5	6552.6	−3199.7	1.82	1	0.177
4	Hand/Arm x FPIQ Kin	1	6432.7	6553.8	−3200.3	0.61	1	0.436
5	Hand/Arm x FPIQ Position	1	6433.2	6554.3	−3200.6	0.08	1	0.772
6	Hand/Arm x FPIQ Action	1	6432.0	6553.1	−3200.0	1.30	1	0.254
7	Hand/Arm x FPIQ Object	1	6430.6	6551.8	−3199.3	2.67	1	0.102
8	Hand/Arm x HLJT LISAS	1	6432.2	6553.3	−3200.1	1.15	1	0.284

Note. AIC= Akaike information criterion; BIC = Bayesian information criterion; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; FPIQ = Florida Praxis Imagery Questionnaire; KIN = Kinesthetic; HLJT LISAS = linear speed accuracy scores from palm-up, fingers-down trials of the Hand Laterality Judgement Task. All models included fixed effects of Hand/arm action strength, EHI, VMIQ-2, all FPIQ subscales, and HLJT LISAS. Models 2–8 include the respective interaction listed in the column "interaction". * $p < .05$ uncorrected.

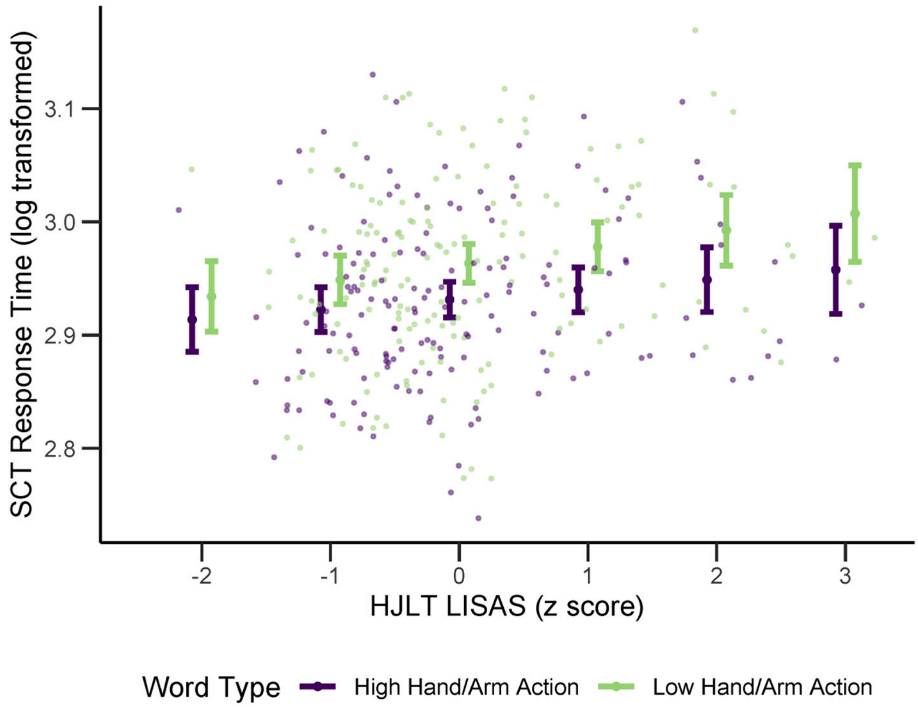

Fig. 5. Motor imagery and hand/arm action strength interaction effects on SCT response times derived from estimated marginal means for high and low hand/arm action strength verbs. Error bars represent 95% confidence intervals. Points represent observed participant mean response times for high and low hand/arm action verbs. SCT = Syntactic Classification Task; HJLT LISAS = linear speed accuracy scores on palm-up, fingers-down trials of the Hand Laterality Judgement Task.

Table 8
Mixed effects models predicting hand/arm action strength effects on SCT response times and accuracy.

	Linear Regression – Response Time			Logistic Regression – Accuracy		
Fixed Effects	*b*	95% *CI*	*p*	*OR*	95% *CI*	*p*
Intercept	2.96	[2.95, 2.98]	< 0.001*	18.67	[13.10, 26.62]	< 0.001*
Hand/Arm Action	−0.03	[−0.05, −0.02]	< 0.001*	2.68	[1.75, 4.11]	< 0.001*
EHI	0.00	[−0.01, 0.01]	0.927	0.91	[0.73, 1.13]	0.402
VMIQ-2	−0.01	[−0.02, 0.00]	0.110	0.99	[0.80, 1.23]	0.955
FPIQ Kin	0.01	[−0.01, 0.02]	0.418	1.05	[0.84, 1.32]	0.671
FPIQ Position	−0.01	[−0.02, 0.01]	0.283	1.27	[0.99, 1.63]	0.058
FPIQ Action	−0.00	[−0.02, 0.01]	0.973	0.95	[0.73, 1.25]	0.736
FPIQ Object	−0.01	[−0.02, 0.01]	0.258	1.03	[0.79, 1.36]	0.813
HLJT LISAS	0.01	[0.00, 0.03]	0.029*	0.99	[0.80, 1.23]	0.947
Word Type*HLJT LISAS	−0.01	[−0.01,-0.00]	0.036*	0.88	[0.76, 1.02]	0.093
Random Effects	Variance	*SD*	*r*	Variance	*SD*	
Participant intercept	0.01	0.08		1.47	1.21	
Hand/Arm slope	0.00	0.02	−0.52	0.33	0.57	
Item Intercept	0.00	0.04		0.86	0.93	
EHI	–	–	–	0.02	0.15	
FPIQ Kin	–	–	–	0.01	0.12	
FPIQ Object	0.00	0.01	−0.06	0.04	0.21	
Residual	0.02	0.14		3.29		
Model Fit	Marginal	Conditional		Marginal	Conditional	
R^2	0.024	0.289		0.053	0.445	

Note. CI = confidence interval; *OR* = odds ratio; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; FPIQ = Florida Praxis Imagery Questionnaire; Kin = Kinesthetic; HLJT LISAS = linear speed accuracy scores for palm-up, fingers-down trials of the Hand Laterality Judgement Task. *SD* = standard deviation. Hand/arm action strength is a binary variable with verbs with low hand/arm action strength ratings as the reference group (0) and verbs with high hand/arm action strength ratings as the focus group (1). Accuracy is a binary dependent variable with incorrect responses as the reference group (0) and correct responses as the focus group (1). The marginal R^2 includes only the variance from the fixed effects and the conditional R^2 includes variance from both the fixed and random effects. The model equation for response time was: RT ~ Hand/Arm Action + EHI + VMIQ-2 + FPIQ A + FPIQ B + FPIQ C + FPIQ D + Hand/Arm Action*HLJT LISAS + (1 + Hand/Arm Action|Participant) + (1 + FPIQ D|Item). The model equation for accuracy was: Acc ~ Hand/Arm Action + EHI + VMIQ-2 + FPIQ A + FPIQ B + FPIQ C + FPIQ D + HLJT LISA + (1 + Hand/Arm Action||Participant) + (1 + EHI + FPIQ A + FPIQ D||Item). *p*-values for fixed effects in the linear mixed effects model are calculated using Satterthwaite's method. *N* participants = 157, *N* words = 93. * *p* < .05 uncorrected.

action strength on accuracy (correct coded as 1, incorrect coded as 0). Responses to verbs with high hand/arm action strength ratings were just over 2.6 times as likely to be accurate compared to verbs with low hand/arm action strength ratings. There were no significant interactions between hand/arm action strength ratings and the motor imagery measures.

For the embodiment SCT models we entered fixed effects of embodiment (high coded as 1, low coded as 0), TAMI scores, and MBRT LISAS (see Table 9 for fixed effect model comparisons). The best fitting model for response time was: RT ~ Embodiment + EHI + VMIQ-2 + TAMI + MBRT LISAs + (1 + Embodiment||Participant) + (1 + EHI + VMIQ-2 + MBRT LISAS||Item). This model (Table 10) revealed a significant effect of embodiment on SCT response times, indicating faster responses to high embodiment verbs ($M = 1046.3$ ms, $SD = 451.3$) compared to low embodiment verbs ($M = 1087$ ms, $SD = 479.7$). There were no significant interactions between embodiment and the motor imagery measures.

The best fitting model for accuracy was: Acc ~ Embodiment + EHI + VMIQ-2 + TAMI + LISA + (1 + Embodiment |Participant) + (1 + EHI|| Item). This model (Table 9) revealed a significant effect of TAMI scores on SCT accuracy, indicating that for each unit increase in TAMI score (indicating better motor imagery) participants were 1.24 times as likely to respond accurately. There were no significant interactions between embodiment and the motor imagery measures.

3.3. Experiment 2 discussion

In Experiment 2, we tested whether the previously observed interactions between FPIQ scores and BOI were due to the representation of hands in imagery and simulation, or due to the representation of skilled, object-directed actions in imagery and simulation. We found an effect of hand/arm action strength, wherein verbs high in hand/arm action strength ratings were processed more quickly and accurately than verbs low in hand/arm action strength ratings. We also observed a significant interaction between one of the hand motor imagery measures and hand/arm action word processing. Only participants with the fastest performance on the HLJT (indicating better imagery) did not significantly differ in their response times to high and low hand/arm action strength verbs. In contrast, participants with the slowest performance on the HLJT (indicating poorer imagery) showed the largest difference in how long they took to respond to high and low hand/arm action strength words. Thus, although hand imagery ability interacts with sensorimotor effects in semantic processing, the nature and direction of the interaction differs from that observed in the BOI SCT in Experiment 1, suggesting different underlying processes.

We found no relationships between whole body imagery ability and embodied effects in the embodiment SCT. We did observe the anticipated effect of relative embodiment on response times, where verbs with higher embodiment ratings were processed more quickly, suggesting these words benefit from sensorimotor simulation during semantic processing. These relative embodiment effects replicate those reported previously (Sidhu et al., 2014; Sidhu & Pexman, 2016). However, there was no interaction between the individual differences in motor imagery measures and embodiment effects in the SCT.

4. General discussion

The purpose of the present study was to investigate sensorimotor simulation of actions during word processing by testing for interactions between motor imagery tasks and sensorimotor semantic processing. First, it should be noted that the results replicate previous findings of sensorimotor effects in language processing (e.g., the BOI effect for nouns; Pexman et al., 2019; the embodiment effect for verbs; Sidhu et al., 2014). Second, we observed additional sensorimotor effects, for foot/leg action strength ratings (Experiment 1) and hand/arm action strength ratings (Experiment 2). These involve faster and more accurate semantic processing for verbs higher in either hand/arm or foot/leg action meaning (Lynott et al., 2020) and demonstrate that sensorimotor information (i.e., hand/arm or foot/leg -action strength) is recruited when processing verbs, which is consistent with previous work examining effector-specific response time differences and congruency effects in action verb processing (e.g., Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Scorolli & Borghi, 2007). The results of the interactions from Experiment 1 point to relationships between motor imagery and BOI effects in language processing, while the results from Experiment 2 suggest that those relationships are limited and specific. We first summarize those results, and then offer implications for our understanding of mechanisms of motor imagery and sensorimotor simulation in language processing.

We replicated the previously observed interaction between BOI and the FPIQ position subscale (Muraki & Pexman, 2021), wherein participants with better FPIQ position imagery scores show a BOI effect and participants with poorer FPIQ position imagery scores show a null BOI effect. We also observed a new interaction effect between BOI and FPIQ Kinesthetic subscale on response accuracy (Experiment 1), where participants with better FPIQ Kinesthetic scores were more accurate when responding to high BOI nouns and less accurate when responding to low BOI nouns. These findings suggest that motor imagery and simulations during semantic processing do share some mechanisms. For example, sensorimotor simulations may share mechanisms with the earliest stage of motor imagery, when an internal model for a known action is activated, but not share mechanisms with later stages of motor imagery, such as when the consequences of an action are imagined (Rieger, Boe, Ingram, Bart, & Dahm, 2023). Furthermore, the presence of a BOI effect

Table 9
Model comparisons for embodiment SCT fixed effect interactions using likelihood ratio tests.

Model	Interaction	Compared Model	*AIC*	*BIC*	*log likelihood*	χ^2	*df*	*p*
Response Time Models								
1	NA		192,920	193,017	−96,447			
2	Embodiment x EHI	1	192,921	193,025	−96,446	1.44	1	0.231
3	Embodiment x VMIQ-2	1	192,920	193,025	−96,446	2.04	1	0.153
4	Embodiment x TAMI	1	192,921	193,025	−96,446	1.44	1	0.230
5	Embodiment x MBRT LISAS	1	192,921	193,025	−96,466	1.34	1	0.248
Accuracy Models								
1	NA		8988.3	9079.4	−4482.1			
2	Embodiment x EHI	1	8988.1	9086.9	−4481.1	2.17	1	0.140
3	Embodiment x VMIQ-2	1	8989.4	9088.1	−4481.7	0.90	1	0.343
4	Embodiment x TAMI	1	8990.3	9089.0	−4482.1	0.02	1	0.892
5	Embodiment x MBRT LISAS	1	8990.3	9089.0	−4482.1	0.04	1	0.847

Note. AIC= Akaike information criterion; *BIC* = Bayesian information criterion; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; TAMI = Test of Ability in Movement Imagery; MBRT LISAS = linear speed accuracy score for front-view, upside-down leg trials of the Mental Body Rotation Task. All models included fixed effects of Embodiment, EHI, VMIQ-2, TAMI, and MBRT LISAS. Models 2–5 include the respective interaction listed in the column “interaction”.

Table 10
Mixed effects models predicting embodiment effects on SCT response times and accuracy.

	Linear Regression - Response Time			Logistic Regression - Accuracy		
Fixed Effects	*b*	95% *CI*	*p*	*OR*	95% *CI*	*p*
Intercept	3.01	[2.99, 3.02]	< 0.001*	12.47	[8.98, 17.32]	< 0.001*
Embodiment	−0.02	[−0.03, −0.00]	0.011*	1.41	[0.98, 2.02]	0.066
EHI	−0.01	[−0.02, 0.01]	0.304	1.07	[0.88, 1.30]	0.481
VMIQ-2	0.00	[−0.01, 0.01]	0.938	1.00	[0.82, 1.21]	0.966
TAMI	0.01	[−0.01, 0.02]	0.495	1.24	[1.01, 1.52]	0.041*
MBRT LISAS	0.01	[−0.00, 0.02]	0.202	0.96	[0.79, 1.17]	0.697
Random Effects	Variance	*SD*		Variance	*SD*	*r*
Participant intercept	0.01	0.08		1.82	1.35	
Embodiment slope	0.00	0.02		0.47	0.69	−0.57
Item Intercept	0.00	0.03		0.60	0.77	
EHI slope	0.00	0.01		–	–	–
VMIQ-2 slope	0.00	0.00		–	–	–
TAMI slope	–	–		0.01	0.10	0.38
MBRT LISAS slope	0.00	0.01		–	–	–
Residual	0.02	0.14		3.29	–	
Model Fit	Marginal	Conditional		Marginal	Conditional	
R^2	0.008	0.274		0.015	0.402	

Note. CI = confidence interval; *OR* = odds ratio; EHI = Edinburgh Handedness Inventory; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; TAMI = Test of Ability in Movement Imagery; MBRT LISAS = linear speed accuracy scores for front-view, upside-down leg trials of the Mental Body Rotation Task. Embodiment is a binary variable with low embodiment verbs as the reference group (0) and high embodiment verbs as the focus group (1). Accuracy is a binary dependent variable with inaccurate responses as the reference group (0) and accurate responses as the focus group (1). The marginal R^2 includes only the variance from the fixed effects and the conditional R^2 includes variance from both the fixed and random effects. The model equation for response time was: RT ~ Embodiment + EHI + VMIQ-2 + TAMI + MBRT LISAs + (1 + Embodiment||Participant) + (1 + EHI + VMIQ-2 + MBRT LISAS||Item). The model equation for accuracy was: Acc ~ Embodiment + EHI + VMIQ-2 + TAMI + LISA + (1 + Embodiment |Participant) + (1 + EHI||Item). *p*-values for fixed effects in the linear mixed effects model are calculated using Satterthwaite's method. *N* participants = 157, *N* words = 95. * *p* < .05 uncorrected.

for people with better FPIQ position scores suggests that they may rely to a greater extent on simulation to ground and process word meaning, and that they are more affected when words lack associated sensorimotor experience. This would support multiple representation theories of semantic cognition, which propose that word meaning can be grounded in many types of experience including motor, perceptual, emotional, social, and linguistic experience (Barsalou, 2009; Borghi et al., 2019). The theories suggest that variations in how these different aspects of word meaning are recruited during semantic processing may reflect individual differences, like in motor imagery ability.

In the hand/arm action strength SCT, we observed an interaction wherein only participants with the fastest responses on the most difficult trials of the HLJT showed no significant difference in their response times to high and low hand/arm action strength verbs, whereas participants with the slowest responses showed the largest difference between the high and low hand/arm action strength verbs. This specific interaction effect was not predicted, but one possible explanation is that people with less vivid and/or accurate motor imagery have more difficulty when a task decision requires an assessment of action meaning (such as is it a verb?). This may have a greater effect on low hand/arm action verb trials, which afford less clear motor representations than high hand/arm action verb trials.

We observed no interaction between foot/leg motor imagery and foot/leg action verb processing, and no interaction between whole body motor imagery and embodied verb processing, despite observing sensorimotor semantic effects in both tasks. It is possible that the present study had insufficient power to detect such interaction effects, as testing individual difference interaction effects in language processing can require a minimum of 1000 participants (Bernabeu, 2022). Another possibility for the lack of interaction between whole body imagery and sensorimotor effects in semantic processing is that the relative embodiment dimension for verbs captures more than motor experience. This measure is defined as quantifying the degree to which a verb's meaning refers to actions, states, or relations that easily involve the human body (Sidhu et al., 2014). It is possible that in addition to motor simulations, embodied meaning simulates interoceptive, proprioceptive, and visual experience. Furthermore, it is possible that potential shared mechanisms between sensorimotor simulations and unconscious motor imagery are not dependent on one's relative motor imagery ability. Thus, these sensorimotor effects would not be sensitive to individual differences in motor imagery ability. This explanation is consistent with other studies that have observed mu frequency desynchronization (associated with motor imagery; Pineda, 2005) during language processing (Alemanno et al., 2012; Bechtold, Ghio, Lange, & Bellebaum, 2018; Moreno et al., 2015; Moreno, de Vega, & León, 2013; Niccolai et al., 2014; van Elk, van Schie, Zwaan, & Bekkering, 2010).

Our results point to the inference that sensorimotor simulations engaged during language processing may be subserved by two systems: one for skilled, object-directed actions and another for motor representations. This is consistent with the proposal that there are unique systems dedicated to skilled, object-directed action representations (Binkofski & Buxbaum, 2013; Buxbaum & Kalénine, 2010) and with evidence that there are canonical neurons which fire in response to manipulable objects. These canonical neurons are functionally distinct from the human mirror neuron system, which responds to viewing action and is thought to be implicated in motor imagery (Oztop & Arbib, 2002). The present findings suggest that imagery for object-directed actions might share mechanisms with sensorimotor simulations that occur when processing words that refer to easy-to-interact-with entities.

Our findings are not consistent with those of previous research which have been taken to suggest that implicit, unconscious sensorimotor simulations during language processing and mental imagery more generally are distinct from one another because mental imagery is a conscious activity (Willems et al., 2009; Willems, Hagoort, & Casasanto, 2010; Zwaan & Pecher, 2012). Instead, our findings are consistent with the possibility that there are implicit, unconscious mechanisms that contribute to both sensorimotor simulations and mental imagery (Kwok, Leys, Koenig-Robert, & Pearson, 2019; Pearson, 2019; Pearson, Naselaris, Holmes, & Kosslyn, 2015) and motor imagery more specifically (Grush, 2004). Some representations of skilled, object-directed action information are engaged in an unconscious, involuntary manner to support how we interact with objects in the world (Buxbaum & Kalénine, 2010). Future research should systematically investigate if unconscious motor imagery or object-directed motor imagery exists, and how it may differ from consciously generated imagery. One approach to testing this question is to examine whether sensorimotor simulation effects in language processing are present in aphantasia, characterized as an absence of the conscious experience of mental imagery (Zeman, Dewar, & Della Sala, 2015). If sensorimotor effects are still observed in language processing in individuals with aphantasia, it would suggest that aphantasia disrupts the conscious generation of mental imagery, but may leave intact unconscious imagery, allowing sensorimotor simulation effects to persist.

A main limitation of the present study is that it is correlational. Our methods cannot determine whether there is a causal relationship between hand motor imagery and sensorimotor simulations during language processing. Furthermore, as mentioned, such correlational studies also require large sample sizes in order to detect individual difference effects and interactions (Bernabeu, 2022). However, the results offer promising new clues about a potential mechanism of sensorimotor simulation and lay the groundwork for future research investigating a causal relationship.

Another potential limitation of our methodology is that the FPIQ (Ochipa et al., 1997), VMIQ-2 (Dahm, 2022; Roberts et al., 2008), and TAMI (Madan & Singhal, 2013) are written questionnaires. In these language-based motor imagery measures, performance may reflect individual variability in sensorimotor simulations when reading the questionnaire rather than individual differences in motor imagery per se. However, the MBRT (Dahm, 2020; Dahm et al., 2022) and HJLT (Parsons, 1987) are non-linguistic measures and thus not subject to the same limitation. The fact that we observed interactions between HLJT performance and hand/arm action strength effects in semantic processing suggests that the interactions are likely driven by differences in motor imagery rather than language simulations. Furthermore, while we have used four different methods to assess dimensions of motor imagery most relevant to the sensorimotor effects in question, measuring motor imagery vividness and ability is challenging due to the overlap with other processes such as visual imagery and mental rotation ability (Madan & Singhal, 2012). Overall, motor imagery measures require further refinement (Dahm, 2020).

The exact nature of the shared mechanisms between motor imagery and sensorimotor simulations in language processing is yet to be identified. However, the present study represents a substantial advance by providing evidence of a relationship between individual differences in hand-specific motor imagery and hand/arm -specific sensorimotor effects in language processing, through both a replication and novel interaction effects. As such, the results are consistent with the notion that object-directed motor imagery recruiting canonical neurons is a plausible mechanism for simulation (Binkofski & Buxbaum, 2013; Buxbaum & Kalénine, 2010; Oztop & Arbib, 2002), addressing an underspecified component of most grounded theories of semantic representation. The results also provide new clues about the ways in which individual, contextual, and environmental factors are recruited for the purposes of concept representation.

Author note

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), in the form of a Postgraduate Scholarship - Doctoral to EJM and a Discovery Grant to PMP. We have no known conflict of interest to disclose.

CRediT authorship contribution statement

Emiko J. Muraki: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Stephan F. Dahm:** Conceptualization, Resources, Writing – review & editing. **Penny M. Pexman:** Conceptualization, Writing – review & editing, Supervision.

Data availability

We have shared our data on OSF and linked the OSF page in the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2023.105589.

References

Alemanno, F., Houdayer, E., Cursi, M., Velikova, S., Tettamanti, M., Comi, G., … Leocani, L. (2012). Action-related semantic content and negation polarity modulate motor areas during sentence reading: An event-related desynchronization study. *Brain Research, 1484*, 39–49. https://doi.org/10.1016/j.brainres.2012.09.030

Anderson, M. L. (2010). Neural reuse: A fundamental organizational principle of the brain. *Behavioral and Brain Sciences, 33*(4), 245–266. https://doi.org/10.1017/S0140525X10000853

Balota, D. A., Yap, M. J., Hutchison, K. A., Cortese, M. J., Kessler, B., Loftis, B., … Treiman, R. (2007). The English lexicon project. *Behavior Research Methods, 39*(3), 445–459. https://doi.org/10.3758/BF03193014

Barsalou, L. W. (2009). Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 364*(1521), 1281–1289. https://doi.org/10.1098/rstb.2008.0319

Barsalou, L. W. (2016). On staying grounded and avoiding quixotic dead ends. *Psychonomic Bulletin & Review, 23*(4), 1122–1142. https://doi.org/10.3758/s13423-016-1028-3

Barsalou, L. W. (2020). Challenges and opportunities for grounding cognition. *Journal of Cognition, 3*(1), 31. https://doi.org/10.5334/joc.116

Barsalou, L. W., Santos, A., Simmons, W. K., & Wilson, C. D. (2008). Language and simulation in conceptual processing. In M. De Vega, A. M. Glenberg, & A. C. Graesser (Eds.), *Symbols, embodiment, and meaning* (pp. 245–283). Oxford University Press.

Bates, D., Kliegl, R., Vasishth, S., & Baayen, R. H. (2015). *Parsimonious mixed models*.

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

Bechtold, L., Ghio, M., Lange, J., & Bellebaum, C. (2018). Event-related desynchronization of mu and beta oscillations during the processing of novel tool names. *Brain and Language, 177–178*, 44–55. https://doi.org/10.1016/j.bandl.2018.01.004

Bernabeu, P. (2022). *Language and sensorimotor simulation in conceptual processing: Multilevel analysis and statistical power*. Unpublished doctoral dissertation. Lancaster University https://eprints.lancs.ac.uk/id/eprint/177833/.

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

Borghi, A. M., Barca, L., Binkofski, F., Castelfranchi, C., Pezzulo, G., & Tummolini, L. (2019). Words as social tools: Language, sociality and inner grounding in abstract concepts. *Physics of Life Reviews, 29*, 120–153. https://doi.org/10.1016/j.plrev.2018.12.001

Borghi, A. M., Binkofski, F., Castelfranchi, C., Cimatti, F., Scorolli, C., & Tummolini, L. (2017). The challenge of abstract concepts. *Psychological Bulletin, 143*(3), 263–292. https://doi.org/10.1037/bul0000089

Bridges, D., Pitiot, A., MacAskill, M. R., & Peirce, J. W. (2020). The timing mega-study: Comparing a range of experiment generators, both lab-based and online. *PeerJ, 8*, Article e9414. https://doi.org/10.7717/peerj.9414

Brysbaert, M., Mandera, P., McCormick, S. F., & Keuleers, E. (2019). Word prevalence norms for 62,000 English lemmas. *Behavior Research Methods, 51*(2), 467–479. https://doi.org/10.3758/s13428-018-1077-9

Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*(4), 977–990. https://doi.org/10.3758/BRM.41.4.977

Brysbaert, M., Warriner, A. B., & Kuperman, V. (2014). Concreteness ratings for 40 thousand generally known English word lemmas. *Behavior Research Methods, 46*(3), 904–911. https://doi.org/10.3758/s13428-013-0403-5

Buxbaum, L. J., & Kalénine, S. (2010). Action knowledge, visuomotor activation, and embodiment in the two action systems. *Annals of the New York Academy of Sciences, 1191*(1), 201–218. https://doi.org/10.1111/j.1749-6632.2010.05447.x

Cayol, Z., & Nazir, T. A. (2020). Why language processing recruits modality specific brain regions: It is not about understanding words, but about modelling situations. *Journal of Cognition, 3*(1), 35. https://doi.org/10.5334/joc.124

Cayol, Z., Rotival, C., Paulignan, Y., & Nazir, T. A. (2020). "Embodied" language processing: Mental motor imagery aptitude predicts word-definition skill for high but not for low imageable words in adolescents. *Brain and Cognition, 145*, Article 105628. https://doi.org/10.1016/j.bandc.2020.105628

Connell, L. (2019). What have labels ever done for us? The linguistic shortcut in conceptual processing. *Language, Cognition and Neuroscience, 34*(10), 1308–1318. https://doi.org/10.1080/23273798.2018.1471512

Cortese, M. J., & Fugett, A. (2004). Imageability ratings for 3,000 monosyllabic words. *Behavior Research Methods, Instruments, & Computers, 36*(3), 384–387. https://doi.org/10.3758/bf03195585

Cortese, M. J., & Schock, J. (2013). Imageability and age of acquisition effects in disyllabic word recognition. *The Quarterly Journal of Experimental Psychology, 66*(5), 946–972. https://doi.org/10.1080/17470218.2012.722660

Dahm, S. F. (2020). On the assessment of motor imagery ability: A research commentary. *Imagination, Cognition and Personality, 39*(4), 397–408. https://doi.org/10.1177/0276236619836091

Dahm, S. F. (2022). Validation of a computer-based version of the vividness of movement imagery questionnaire. *Psychological Test Adaptation and Development, 3*(1), 10–22. https://doi.org/10.1027/2698-1866/a000022

Dahm, S. F., Muraki, E. J., & Pexman, P. M. (2022). Hand and foot selection in mental body rotations involves motor-cognitive interactions. *Brain Sciences, 12*(11), 1500. https://doi.org/10.3390/brainsci12111500

Dalla Volta, R., Fabbri-Destro, M., Gentilucci, M., & Avanzini, P. (2014). Spatiotemporal dynamics during processing of abstract and concrete verbs: An ERP study. *Neuropsychologia*, *61* (Alexander, M.P., Benson, D.F. (1993). The aphasias and related disturbances). In R. J. Joynt (Ed.), *Clinical neurology* (pp. 1–58). Philadelphia: Lipincott JB.Aziz-Zadeh, L., Wilson, S.M., Rizzolatti, G., Iacoboni, M. (2006). Congruent embodied representa), 163–174 https://doi.org/10.1016/j.neuropsychologia.2014.06.019.

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

Ehrsson, H. H., Geyer, S., & Naito, E. (2003). Imagery of voluntary movement of fingers, toes, and tongue activates corresponding body-part-specific motor representations. *Journal of Neurophysiology, 90*(5), 3304–3316. https://doi.org/10.1152/jn.01113.2002

van Elk, M., van Schie, H. T., Zwaan, R. A., & Bekkering, H. (2010). The functional role of motor activation in language processing: Motor cortical oscillations support lexical-semantic retrieval. *NeuroImage, 50*(2), 665–677. https://doi.org/10.1016/j.neuroimage.2009.12.123

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

Glover, S., & Baran, M. (2017). The motor-cognitive model of motor imagery: Evidence from timing errors in simulated reaching and grasping. *Journal of Experimental Psychology: Human Perception and Performance, 43*(7), 1359–1375. https://doi.org/10.1037/xhp0000389

Goh, W. D., Yap, M. J., Lau, M. C., Ng, M. M. R., & Tan, L.-C. (2016). Semantic richness effects in spoken word recognition: A lexical decision and semantic categorization megastudy. *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.00976

Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *Behavioral and Brain Sciences, 27*(3), 377–396. https://doi.org/10.1017/S0140525X04000093

Habacha, H., Molinaro, C., & Dosseville, F. (2014). Effects of gender, imagery ability, and sports practice on the performance of a mental rotation task. *The American Journal of Psychology, 127*(3), 313–323. https://doi.org/10.5406/amerjpsyc.127.3.0313

Hauk, O., Johnsrude, I., & Pulvermuller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*, 301–307. https://doi.org/10.1016/S0896-6273(03)00838-9

Heard, A., Madan, C. R., Protzner, A. B., & Pexman, P. M. (2019). Getting a grip on sensorimotor effects in lexical-semantic processing. *Behavior Research Methods, 51* (1), 1–13. https://doi.org/10.3758/s13428-018-1072-1

Hintz, F., Jongman, S. R., Dijkhuis, M., Van't Hoff, V., McQueen, J. M., & Meyer, A. S. (2020). Shared lexical access processes in speaking and listening? An individual differences study. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 46*(6), 1048–1063. https://doi.org/10.1037/xlm0000768

Hoyek, N., Di Rienzo, F., Collet, C., Creveaux, T., & Guillot, A. (2014). Hand mental rotation is not systematically altered by actual body position: Laterality judgment versus same–different comparison tasks. *Attention, Perception, & Psychophysics, 76*(2), 519–526. https://doi.org/10.3758/s13414-013-0577-z

Ibáñez, A., Kühne, K., Miklashevsky, A., Monaco, E., Muraki, E., Ranzini, M., … Tuena, C. (2022, August 12). *Ecological meanings: A consensus paper on individual differences and contextual influences in embodied language*. https://doi.org/10.31219/osf.io/ej5y3

Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. Oxford University Press.

Juhasz, B. J., & Yap, M. J. (2013). Sensory experience ratings for over 5,000 mono- and disyllabic words. *Behavior Research Methods, 45*(1), 160–168. https://doi.org/10.3758/s13428-012-0242-9

Klepp, A., Weissler, H., Niccolai, V., Terhalle, A., Geisler, H., Schnitzler, A., & Biermann-Ruben, K. (2014). Neuromagnetic hand and foot motor sources recruited during action verb processing. *Brain and Language, 128*(1), 41–52. https://doi.org/10.1016/j.bandl.2013.12.001

Kuhnke, P., Beaupain, M. C., Arola, J., Kiefer, M., & Hartwigsen, G. (2022). Meta-analytic evidence for a novel hierarchical model of conceptual processing. *Neuroscience & Biobehavioral Reviews, 104994*. https://doi.org/10.1016/j.neubiorev.2022.104994

Kuperman, V., Stadthagen-Gonzalez, H., & Brysbaert, M. (2012). Age-of-acquisition ratings for 30,000 English words. *Behavior Research Methods, 44*(4), 978–990. https://doi.org/10.3758/s13428-012-0210-4

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13). https://doi.org/10.18637/jss.v082.i13

Kwok, E. L., Leys, G., Koenig-Robert, R., & Pearson, J. (2019). Measuring thought-control failure: Sensory mechanisms and individual differences. *Psychological Science, 30*(6), 811–821. https://doi.org/10.1177/0956797619837204

Lawrence, S. J. D., Van Mourik, T., Kok, P., Koopmans, P. J., Norris, D. G., & De Lange, F. P. (2018). Laminar Organization of Working Memory Signals in human visual cortex. *Current Biology, 28*(21), 3435–3440.e4. https://doi.org/10.1016/j.cub.2018.08.043

Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means (R package version 1.7.5) https://CRAN.R-project.org/package=emmeans.

Lorey, B., Naumann, T., Pilgramm, S., Petermann, C., Bischoff, M., Zentgraf, K., Stark, R., Vaitl, D., & Munzert, J. (2013). How equivalent are the action execution, imagery, and observation of intransitive movements? Revisiting the concept of somatotopy during action simulation. *Brain and Cognition, 81*(1), 139–150. https://doi.org/10.1016/j.bandc.2012.09.011

Lüdecke, D. (2021). sjPlot: Data visualization for statistics in social science (R package version 2.8.7) https://CRAN.R-project.org/package=sjPlot.

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., & Makowski, D. (2021). Performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software, 6*(60), 3139. https://doi.org/10.21105/joss.03139

Lynott, D., Connell, L., Brysbaert, M., Brand, J., & Carney, J. (2020). The Lancaster sensorimotor norms: Multidimensional measures of perceptual and action strength for 40,000 English words. *Behavior Research Methods, 52*(3), 1271–1291. https://doi.org/10.3758/s13428-019-01316-z

Madan, C. R., & Singhal, A. (2012). Motor imagery and higher-level cognition: Four hurdles before research can sprint forward. *Cognitive Processing, 13*(3), 211–229. https://doi.org/10.1007/s10339-012-0438-z

Madan, C. R., & Singhal, A. (2013). Introducing TAMI: An objective test of ability in movement imagery. *Journal of Motor Behavior, 45*(2), 153–166. https://doi.org/10.1080/00222895.2013.763764

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex, 48*(7), 788–804. https://doi.org/10.1016/j.cortex.2010.11.002

Moreno, I., de Vega, M., & León, I. (2013). Understanding action language modulates oscillatory mu and beta rhythms in the same way as observing actions. *Brain and Cognition, 82*(3), 236–242. https://doi.org/10.1016/j.bandc.2013.04.010

Moreno, I., de Vega, M., León, I., Bastiaansen, M., Glen Lewis, A., & Magyari, L. (2015). Brain dynamics in the comprehension of action-related language. A time-frequency analysis of mu rhythms. *NeuroImage, 109*, 50–62. https://doi.org/10.1016/j.neuroimage.2015.01.018

Munzert, J., Lorey, B., & Zentgraf, K. (2009). Cognitive motor processes: The role of motor imagery in the study of motor representations. *Brain Research Reviews, 60*(2), 306–326. https://doi.org/10.1016/j.brainresrev.2008.12.024

Muraki, E. J., & Pexman, P. M. (2021). Simulating semantics: Are individual differences in motor imagery related to sensorimotor effects in language processing? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 47*(12), 1939–1957. https://doi.org/10.1037/xlm0001039

Muraki, E. J., Sidhu, D. M., & Pexman, P. M. (2022). Heterogenous abstract concepts: Is ponder different from dissolve? *Psychological Research, 86*, 2478–2494. https://doi.org/10.1007/s00426-020-01398-x

Niccolai, V., Klepp, A., Weissler, H., Hoogenboom, N., Schnitzler, A., & Biermann-Ruben, K. (2014). Grasping hand verbs: Oscillatory Beta and Alpha correlates of action-word processing. *PLoS One, 9*(9), Article e108059. https://doi.org/10.1371/journal.pone.0108059

Ochipa, C., Rapcsak, S. Z., Maher, L. M., Gonzalez Rothi, L. J., Bowers, D., & Heilman, K. M. (1997). Selective deficit of praxis imagery in ideomotor apraxia. *Neurology, 49*(2), 474–480. https://doi.org/10.1212/wnl.49.2.474

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

Ostarek, M., & Bottini, R. (2021). Towards strong inference in research on embodiment – Possibilities and limitations of causal paradigms. *Journal of Cognition, 4*(1), 5. https://doi.org/10.5334/joc.139

Oztop, E., & Arbib, M. A. (2002). Schema design and implementation of the grasp-related mirror neuron system. *Biological Cybernetics, 87*(2), 116–140. https://doi.org/10.1007/s00422-002-0318-1

Parsons, L. M. (1987). Imagined spatial transformations of one's hands and feet. *Cognitive Psychology, 19*, 178–241. https://doi.org/10.1016/0010-0285(87)90011-9

Patterson, K., & Lambon Ralph, M. A. (2016). Chapter 61—The hub-and-spoke hypothesis of semantic memory. In G. Hickok, & S. L. Small (Eds.), *Neurobiology of language* (pp. 765–775). Academic Press. https://doi.org/10.1016/B978-0-12-407794-2.00061-4.

Pavan, A., & Baggio, G. (2013). Linguistic representations of motion do not depend on the visual motion system. *Psychological Science, 24*(2), 181–188. https://doi.org/10.1177/0956797612450882

Pearson, J. (2019). The human imagination: The cognitive neuroscience of visual mental imagery. *Nature Reviews Neuroscience, 20*(10), 624–634. https://doi.org/10.1038/s41583-019-0202-9

Pearson, J., Naselaris, T., Holmes, E. A., & Kosslyn, S. M. (2015). Mental imagery: Functional mechanisms and clinical applications. *Trends in Cognitive Sciences, 19*(10), 590–602. https://doi.org/10.1016/j.tics.2015.08.003

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pexman, P. M., Muraki, E., Sidhu, D. M., Siakaluk, P. D., & Yap, M. J. (2019). Quantifying sensorimotor experience: Body-object interaction ratings for more than 9,000 English words. *Behavior Research Methods, 51*(2), 453–466. https://doi.org/10.3758/s13428-018-1171-z

Pineda, J. A. (2005). The functional significance of mu rhythms: Translating "seeing" and "hearing" into "doing". *Brain Research Reviews, 50*(1), 57–68. https://doi.org/10.1016/j.brainresrev.2005.04.005

Pylyshyn, Z. (1980). Computation and cognition: Issues in the foundations of cognitive science. *The Behavioral and Brain Sciences, 3*, 111–169. https://doi.org/10.1017/S0140525X00002053

R Core Team. (2022). *R: A language and environment for statistical computing. (4.2.1)*. R Foundation for Statistical Computing. https://www.R-project.org/.

Ratcliff, R., Thapar, A., & McKoon, G. (2010). Individual differences, aging, and IQ in two-choice tasks. *Cognitive Psychology, 60*(3), 127–157. https://doi.org/10.1016/j.cogpsych.2009.09.001

Rieger, M., Boe, S. G., Ingram, T. G. J., Bart, V. K. E., & Dahm, S. F. (2023). A theoretical perspective on action consequences in action imagery: Internal prediction as an essential mechanism to detect errors. *Psychological Research*. https://doi.org/10.1007/s00426-023-01812-0

Roberts, R., Callow, N., Hardy, L., Markland, D., & Bringer, J. (2008). Movement imagery ability: Development and assessment of a revised version of the vividness of movement imagery questionnaire. *Journal of Sport & Exercise Psychology, 30*, 200–221. https://doi.org/10.1123/jsep.30.2.200

Schock, J., Cortese, M. J., & Khanna, M. M. (2012). Imageability estimates for 3,000 disyllabic words. *Behavior Research Methods, 44*(2), 374–379. https://doi.org/10.3758/s13428-011-0162-0

Schönbrodt, F. D., & Perugini, M. (2013). At what sample size do correlations stabilize? *Journal of Research in Personality, 47*(5), 609–612. https://doi.org/10.1016/j.jrp.2013.05.009

Scorolli, C., & Borghi, A. M. (2007). Sentence comprehension and action: Effector specific modulation of the motor system. *Brain Research, 1130*, 119–124. https://doi.org/10.1016/j.brainres.2006.10.033

Siakaluk, P. D., Pexman, P. M., Sears, C. R., Wilson, K., Locheed, K., & Owen, W. J. (2008). The benefits of sensorimotor knowledge: Body-object interaction facilitates semantic processing. *Cognitive Science, 32*(3), 591–605. https://doi.org/10.1080/03640210802035399

Sidhu, D. M., Kwan, R., Pexman, P. M., & Siakaluk, P. D. (2014). Effects of relative embodiment in lexical and semantic processing of verbs. *Acta Psychologica, 149*, 32–39. https://doi.org/10.1016/j.actpsy.2014.02.009

Sidhu, D. M., & Pexman, P. M. (2016). Is moving more memorable than proving? Effects of embodiment and imagined enactment on verb memory. *Frontiers in Psychology*, *7* (Balota, D. A., Ferraro, F. R., Connor, L. T. (1991). On the early influence of meaning in word recognition: a review of the literature). In P. J. Schwanenflugel (Ed.), *The Psychology of Word Meanings*. Hillsdale, NJ: Erlbaum, 187–222.1991-98708-008Balota.

Stanley, D. (2021). apaTables: Create American Psychological Association (APA) style tables (R package version 2.0.8.) https://CRAN.R-project.org/package=apaTables.

Steggemann, Y., Engbert, K., & Weigelt, M. (2011). Selective effects of motor expertise in mental body rotation tasks: Comparing object-based and perspective transformations. *Brain and Cognition, 76*(1), 97–105. https://doi.org/10.1016/j.bandc.2011.02.013

Stippich, C., Ochmann, H., & Sartor, K. (2002). Somatotopic mapping of the human primary sensorimotor cortex during motor imagery and motor execution by functional magnetic resonance imaging. *Neuroscience Letters, 331*(1), 50–54. https://doi.org/10.1016/S0304-3940(02)00826-1

Taylor, J. E., Beith, A., & Sereno, S. C. (2020). LexOPS: An R package and user interface for the controlled generation of word stimuli. *Behavior Research Methods, 52*(6), 2372–2382. https://doi.org/10.3758/s13428-020-01389-1

Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods, 49*(2), 653–673. https://doi.org/10.3758/s13428-016-0721-5

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., & Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software, 4*(43), 1686. https://doi.org/10.21105/joss.01686

Willems, R. M., Hagoort, P., & Casasanto, D. (2010). Body-specific representations of action verbs: Neural evidence from right- and left-handers. *Psychological Science, 21*(1), 67–74. https://doi.org/10.1177/0956797609354072

Willems, R. M., Toni, I., Hagoort, P., & Casasanto, D. (2009). Neural dissociations between action verb understanding and motor imagery. *Journal of Cognitive Neuroscience, 22*(10), 2387–2400. https://doi.org/10.1162/jocn.2009.21386

Wilson, M. (2008). 19—How did we get from there to Here? An evolutionary perspective on embodied cognition. In P. Calvo, & A. Gomila (Eds.), *Handbook of cognitive science* (pp. 373–393). Elsevier. https://doi.org/10.1016/B978-0-08-046616-3.00019-0.

Yap, M. J., Balota, D. A., Sibley, D. E., & Ratcliff, R. (2012). Individual differences in visual word recognition: Insights from the English lexicon project. *Journal of Experimental Psychology. Human Perception and Performance, 38*(1), 53–79. https://doi.org/10.1037/a0024177

Yarkoni, T., Balota, D., & Yap, M. (2008). Moving beyond Coltheart's N: A new measure of orthographic similarity. *Psychonomic Bulletin & Review, 15*(5), 971–979. https://doi.org/10.3758/PBR.15.5.971

Zeman, A., Dewar, M., & Della Sala, S. (2015). Lives without imagery – Congenital aphantasia. *Cortex, 73*, 378–380. https://doi.org/10.1016/j.cortex.2015.05.019

Zhao, B., & Sala, S. D. (2018). Different representations and strategies in mental rotation. *Quarterly Journal of Experimental Psychology, 71*(7), 1574–1583. https://doi.org/10.1080/17470218.2017.1342670

Zwaan, R. A., & Pecher, D. (2012). Revisiting mental simulation in language comprehension: Six replication attempts. *PLoS One, 7*(12), Article e51382. https://doi.org/10.1371/journal.pone.0051382