THE UNIVERSITY OF CHICAGO

ACTION LANGUAGE UNDERSTANDING REFLECTS BODILY AND SOCIAL EXPERIENCE

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Voor Opa Jan en Oma Lou.

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ABSTRACT

People construct the meaning of words by relying, in part, on neural systems for perception and action. For instance, when people process language about actions, they show body-part specific activation in premotor circuits used for preparing actions. How does premotor cortex contribute to the meaning of action language? In Study 1, I used fMRI to test whether people rely on different kinds of action experience to understand language about their own actions and other people's actions. When left- and right-handers imagined their own unimanual actions, they preferentially activated premotor circuits controlling their dominant hand. By contrast, when imagining other people's actions, premotor activity also reflected how participants typically see others perform those actions. Language-induced imagery for our own actions reflects how we use our own bodies, whereas imagery for others' actions also reflects how others use their bodies. In Study 2, I show that premotor cortex functionally contributes to how well people process action language. tDCS to premotor hand-areas selectively affected how accurately people processed unimanual action verbs (but not abstract verbs): Inhibitory stimulation caused a relative improvement in how people processed manual action verbs, whereas excitatory stimulation caused a relative impairment. In Study 3, I developed corpora of Dutch and English manual action verbs to quantify how people use their hands to perform the actions described by these verbs, and show how these corpora provide a precision-tool to test whether the way in which people simulate a given action verb reflects how they typically use their body to perform that action.

CHAPTER 1

INTRODUCTION

1.1 The meaning of words in mind and brain

How do people understand the meaning of words? According to 20th century models of language processing (Geschwind, 1965; Brown & Hagoort, 2000), people process linguistic meaning by relying on the brain's core language network: Temporal lobe areas process lexical and semantic information, Broca's area processes syntax, and a few additional frontal areas support cognitive control and working memory (for different implementations of this standard model, see e.g. Hagoort, 2005; Poeppel, Emmorey, Hickok, & Pylkkänen, 2012; Friederici, 2012; see also Poeppel, 2017). On this standard view, neural systems that are involved in perception and motor planning only play a role in how people perceive and produce the forms of words, but not in how they process the meanings of words (Mahon & Hickok, 2016).

By contrast, since the turn of the 21st century, theories of embodied cognition have proposed that neural systems for perception and action play a critical role, not only in processing the forms of words, but also in instantiating their meanings: People may understand the meanings of words by relying, in part, on the brain's perceptuo-motor systems to simulate the perceptual and motor experiences that are described by those words (Barsalou, 1999; Pulvermüller, 1999). For instance, when people process a word like "cat", they may activate occipital areas to simulate seeing a cat, tactile systems to simulate touching its fur, and motor systems to simulate how they typically pet the cat.

1.2 Using the motor system to test embodied semantics

So far, most of the empirical support for embodied cognition comes from studies that have tested whether people partially rely on (pre)motor cortex for processing the meaning of action language. The motor system provides an ideal testbed for embodied theories, not only because this system is unambiguously modality-specific (see discussion in Casasanto & Gijssels, 2015), but also because its neural organization follows several well-understood principles. One of these principles is that (pre)motor cortex is somato-topically organized: Specific patches of the cerebral cortex preferentially support actions that are performed with specific body-parts, in a way that is stable across individuals (Penfield & Boldrey, 1937, see also Graziano, 2016). For instance, when people perform actions with their hands, they show activation in hand-areas in premotor cortex, whereas when they perform actions with their legs, they show activation in leg-areas in premotor cortex, and so on.

In addition to its somatotopic specialization, (pre)motor cortex also has hemispheric specialization: Motor areas in each of the cerebral hemispheres are preferentially involved in planning and executing actions that are performed with the contralateral side of the body. That is, left (pre)motor cortex predominantly controls the right side of the body, whereas right (pre)motor cortex predominantly controls the left side of the body (see Serrien, Ivry, & Swinnen, 2006 for additional factors contributing to hemispheric specialization of motor systems).

Because of these two organizational principles, the motor system has proved to be the most fruitful testbed for testing the role of perceptuo-motor simulations in language understanding. First, several neuroimaging studies have found that when people process action language, they not only activate (pre)motor cortex, but they do so in a somatotopic way. That is, when people process different types of action verbs, that describe actions performed with different body-parts, they show a pattern of (pre)motor cortex activation that has a similar effector-specific organization as when they prepare to perform those actions (i.e. verbs like “kick”, “pick”, and “lick” activate leg-, hand- and mouth- areas, respectively; Hauk, Johnsrude, & Pulvermüller, 2004; Tettamanti et al., 2005; Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Boulenger, Hauk, & Pulvermüller, 2008).

Second, by combining the inferential leverage of the motor system’s somatotopy with its hemisphericity, experimenters have been able to determine not only whether people simulate, but also how experience shapes the way in which people simulate. If theories of embodied cognition are correct, and people use the same neural systems to perform actions and to understand language about those actions, then the way in which people understand language should be body-specific: People with different bodies who interact with the world in different ways should also think in correspondingly different ways (i.e. the Body-Specificity Hypothesis; Casasanto, 2009, 2011).

In a test of this hypothesis, Willems and colleagues compared neural activity in left- and right-handers while they processed language describing unimanual actions (e.g. "to write"). Left- and right-handers, who perform the same unimanual actions in different ways, also processed language about those actions in correspondingly different ways. When right-handers read unimanual action verbs, they showed stronger activity in right-hand areas in left premotor cortex (PMC). By contrast, when left-handers read those same verbs, they showed stronger activity in left-hand areas in right PMC (Willems, Hagoort, & Casasanto, 2010). These findings suggest that the way in which people typically perform actions shapes the way in which they understand language about those actions.

1.3 How does the motor system contribute to the meaning of action language?

In the following chapters, I report studies that use the somatotopic and hemispheric specialization of the motor system to investigate how motor simulations are contributing to action language understanding.

In the first study, I ask "Does the way in which people understand action language reflect their bodily as well as their social experience with actions?" When people process language about actions for which no actor is specified (e.g. "to write"), they simulate these actions in a way that reflects how they use their own bodies to perform those actions themselves (Willems, Hagoort, & Casasanto, 2010). Do people understand language about other people's actions by imagining how they perform these actions themselves (i.e. using an egocentric perspective), or how they perceive others performing them (i.e. using an allocentric perspective)? To contrast the ego- and allocentric accounts, this experiment tested action language understanding in people who perform actions one way, but see most others perform those actions another way: left-handers. Since left-handers perform manual actions using their left hand, but see most other people perform those same actions with the right hand, testing them allows us to distinguish between both theoretical alternatives. Left- and right-handers read phrases describing unimanual actions in the MRI scanner, and then imagined those actions. I manipulated the grammatical person of the phrases, so that they either described actions performed by the participants themselves (e.g. "you write") or actions performed by other people (e.g. "she writes"). To determine whether participants were representing the described actions as they would perform them themselves, or as they see others performing them, I contrasted BOLD activity in left and right PMC for each condition, separately for the left- and right-handers.

In the second study, I ask how premotor cortex activity causally contributes to the meaning of action language. One previous neurostimulation study supported a causal contribution of PMC activity to action verb understanding, but the direction of the effect was unexpected: Inhibiting PMC made participants respond faster to action verbs (Willems, Labruna, D'Esposito, Ivry, & Casasanto, 2011). On one possible explanation, inhibitory stimulation to PMC may have improved participants' performance by modulating inhibitory PMC circuits: Depending on the behavioral context, inhibition may be necessary to prevent people from overtly performing the actions named by verbs, rather than covertly simulating them. If this explanation is correct, then inhibitory stimulation to PMC should lead to a relative improvement in action verb processing, whereas excitatory stimulation of the same areas should lead to a relative impairment. In this experiment, right-handers received transcranial Direct Current Stimulation (tDCS) that either inhibited or excited dominant hand-areas in left PMC, and then performed a lexical decision task on unimanual and abstract verbs. We tested whether inhibitory and excitatory tDCS had complementary effects on how well participants processed the meaning of unimanual action verbs, but not on how they processed abstract verbs.

In the final study, I develop a tool for testing whether the way in which people understand language about a given manual action reflects the way they use their hands perform that action. Whereas studies of manual action verb processing typically assume that these verbs describe actions that are either unimanual or bimanual, most manual actions probably show continuous variation in the extent to which they rely on the dominant and non-dominant hands. For instance, even when people perform a prototypical unimanual action like writing, they often also rely on their non-dominant hand to stabilize the writing surface (see Guiard, 1987 for discussion). If actions that are assumed to be performed unimanually with the dominant hand also rely on the non-dominant hand, then this assumption may limit researchers' ability to predict the locus activity in the cortical motor system for a given action, and thereby compromise their ability to use cortical specialization to test theories of action semantics.

Here, I constructed corpora of Dutch and English manual action verbs and measured how participants pantomimed the actions described by these verbs. By quantifying the extent to which participants used their left and right hand to perform each of these actions, I provide a precision tool that allows researchers to control for the variation in how people perform manual actions, and to use this variation to test whether motor simulations reflect the way in which individual actions are performed.

CHAPTER 2

UNDERSTANDING LANGUAGE ABOUT OTHER PEOPLE'S ACTIONS.

2.1 Introduction

How does experience shape the way in which people understand language? According to theories of embodied cognition, people understand language about the world by relying on the same neural systems they use for acting and perceiving (Barsalou, 1999; Pulvermüller, 1999). Much of the empirical support for these theories comes from neuroimaging studies of action language understanding: When people process action verbs, they show somatotopic patterns of activation in motor circuits (e.g. processing verbs like *kick*, *pick*, and *lick* correlates with activation in leg-, hand-, and mouth-areas of (pre)motor cortex; Hauk et al., 2004; Aziz-Zadeh et al., 2006).

If people use the same neural systems to perform actions and to understand language about those actions, then people who interact with the world in different ways should also process language in correspondingly different ways (Casasanto, 2011). To test this prediction, Willems et al. (2010) measured neural activity in left- and right-handed participants while they read verbs describing unimanual actions (e.g. *to write*). Left- and right-handers, who perform unimanual actions differently, also processed language about those actions in correspondingly different ways. When right-handers read unimanual action verbs, they showed increased activity in left premotor cortex (PMC) areas controlling the right hand. By contrast, when left-handers read those same verbs, they showed stronger activity in right PMC areas controlling the left hand (Willems, Hagoort, & Casasanto, 2010). These findings show that, when no actor is specified, people understand language about actions in a way that reflects how they would typically perform those actions themselves.

How do people process language about other people's actions? On one possibility, people understand language about others' actions in a way that reflects how they would typically perform those actions themselves (i.e. from an egocentric perspective). On an alternative possibility, people may understand language about others' actions in a way that reflects how they see others perform those actions (i.e. from an allocentric perspective). For instance, when people process a phrase like *She writes*, the egocentric account predicts that people should show motor system activity consistent with how they usually write, themselves, whereas the allocentric account predicts that they should show motor activity consistent with how they see others write.

One fMRI study set out to directly contrast the egocentric and allocentric accounts. Right-handed participants went into the scanner and read sentences describing either their own actions or other people's actions. The results showed that both types of sentences modulated activity in left primary motor cortex, and that these patterns of activity did not differ when people read language about their own actions and when they read language about other people's actions (Tomasino, Werner, Weiss, & Fink, 2007).

Although the results from Tomasino et al. (2007) appear to support the egocentric account, these data are equally consistent with the allocentric alternative because the study only tested right-handed participants. Since right-handers perform manual actions in the same way as they see most other people perform those actions (i.e. with the right hand), this experiment predicts identical outcomes on the egocentric and allocentric accounts (i.e. increased BOLD in left motor regions controlling the right hand). Yet, the ego- and allocentric accounts can be distinguished by testing people who perform actions in one way, but see others perform those actions in another way: left-handers. Whereas left-handers perform unimanual actions with the left hand, they see (most) others perform those actions with the right hand. Therefore, when left-handers read a sentence about someone else's manual actions, we predict different outcomes for the ego- and allocentric alternatives.

Here, we used fMRI to test whether people adopt an egocentric or an allocentric perspective when performing language-induced motor imagery of others' actions. Left- and right-handed participants went into the MR-scanner, and saw phrases describing unimanual and nonmanual actions. These phrases described actions performed either by the participants themselves (2nd pers. sg., e.g. *you write*) or by other people (3rd pers. sg., e.g. *she writes*). Participants processed the meaning of each phrase in a deep conceptual processing task, vividly imagining the actions described by the phrase. When people process 2nd person unimanual verbs describing their own manual actions, they should rely on the same motor circuits they typically use to perform those actions: Right-handers should show stronger left PMC activity, whereas left-handers should show stronger right PMC activity, thereby replicating Willems et al. (2010). When people process 3rd person unimanual verbs describing other people's actions, right-handers should show stronger left PMC activity, consistent with both the egocentric and the allocentric possibility. Yet, when left-handers imagine actions described by 3rd person unimanual verbs, they should show different patterns of results on the ego- and allocentric possibilities. If the egocentric account is correct, then left-handers should show stronger BOLD in right PMC areas controlling the left hand. By contrast, if the allocentric account is correct, then left-handers should show stronger BOLD in left PMC areas controlling the right hand.

2.2 Method

2.2.1 Participants

37 participants took part in this experiment. Data from 4 participants were excluded for not performing the task or for having fewer than 4 out of 8 usable runs (see discussion of artifacts below). All remaining 33 participants were monolingual native English speakers, of whom 17 were right-handed (M = 72.65, Range = 40 to 100) and 16 were left-handed (M = -80.74, Range = -100 to -42.85), as established by the Edinburgh Handedness Inventory (Oldfield, 1971). Following University of Chicago IRB guidelines, all participants provided informed consent and received $60 for participating.

2.2.2 Materials

We created 192 unique stimuli for this experiment by crossing two factors: Verb type (unimanual vs. nonmanual action verbs) and grammatical person (2nd vs. 3rd person singular). To construct the stimuli, we selected 48 verbs that describe unimanual actions (i.e. actions performed with the dominant hand, e.g. *to write*) and 48 verbs that describe nonmanual actions (i.e. actions performed with effectors other than the hands, e.g. *to run*). Manual and non-manual verbs were matched on ratings of imageability ($\chi^2(1) = 1.49$; $p = .22$). Each of these 96 verbs was presented once in 2nd person singular to describe actions performed by the participants themselves (e.g. *you write*) and once in 3rd person singular to describe actions performed by other people (e.g. *she writes*). To encourage participants to interpret the 3rd person pronoun as referring to other people, we asked participants to indicate their preferred pronouns before the experiment (*he*, *she*, *neither*) and used the non-preferred pronoun for the stimuli (a pronoun was randomly selected for participants who expressed no preference, $n = 1$). Finally, unimanual and nonmanual verbs were matched for word length, number of phonemes, and word frequency: all pairwise comparisons $p > .20$ (word frequency based on COBUILD frequency; Baayen, Piepenbrock, & Gulikers, 1995).

2.2.3 Procedure

Participants went into the MR scanner and imagined the actions described by phrases on the screen. Trials had the following structure. First, participants saw a fixation cross for 500 ms. which was replaced by a stimulus phrase. Then, participants read the phrase, closed their eyes, and imagined the action described by the phrase. Once they had finished imagining the action, participants opened their eyes, the trial ended, and a blank screen was presented for an ISI of 4120 ms (+/- 2060 ms jitter, in 1030 ms steps). An eye-tracker (EyeLink 1000, SR Research, Canada) registered the time points at which participants closed and opened their eyes. The entire paradigm was split into 8 individual runs, with each run containing an equal number of phrases for each condition: 6 unimanual 2nd pers., 6 unimanual 3rd pers., 6 nonmanual 2nd pers., and 6 nonmanual 3rd pers. We selected the stimuli for each run by randomly sampling without replacement from the full set of 192 stimuli. Within each run, the order of stimuli was fully randomized.

2.2.4 fMRI Acquisition & Analysis

We acquired whole-brain EPI data using a 3T Philips Achieva (TR = 2060 ms; TE = 30 ms, Flip angle = 77 Voxel size = 3x3x4 mm^3, .5 mm. inter-slice gap). We also collected a T1-weighted structural scan (TR = 8000 ms, TE= 2002 ms, Voxel size = .9x.9x.9 mm^3). All data were preprocessed using the fMRIPREP preprocessing pipeline (Esteban et al., 2018). Structural data were skull-stripped and spatially normalized using ANTs (v. 2.1.0). Tissue segmentation was performed using Fast (FSL v. 5.0.9). Functional data were motion corrected using mcflirt, and co-registered to subjects' structural data using flirt. Finally, images were normalized to the MNI template using ANTs and spatially smoothed (8mm FWHM) using FSL. Due to complications with the SENSE reconstruction, some runs in our data suffered ghosting artifacts and erratic shifts in slice position. After preprocessing, but prior to analysis, we visually inspected the data and excluded all runs with severe artifacts (N=33 runs excluded in total). Two participants had fewer than 4 out of 8 usable runs, and were excluded from the analyses.

We analyzed the functional data using a random-effects regression analysis in FSL's feat package. At the first level, we modeled hemodynamic responses in each run individually for each condition of interest: 2nd pers. unimanual, 3rd pers. unimanual, 2nd pers. nonmanual, and 3rd pers. nonmanual. BOLD responses were modeled using a double-gamma HRF, with the onset placed at stimulus onset and duration defined as the time between stimulus onset and the time at which participants opened their eyes. We included temporal derivatives for each condition. At the second level, run-wise activity was combined for each subject using a fixed-effects model.

Following Willems et al. (2009; 2010), we tested our a priori predictions by analyzing

BOLD responses in bilateral BA6 (which corresponds to premotor cortex) for the contrasts of interest using a subject-wise ROI analysis. For each subject, we created two 4mm spherical ROIs in cyto-architectonically defined left and right BA6 (BA6 definitions based on FSL's Juelich atlas). Each sphere was centered on the coordinates of the voxel that was maximally activated by the second-level contrast for Unimanual > Nonmanual, for a given subject (collapsing across grammatical person; un-thresholded maps) in each cerebral hemisphere[1]. Each sphere was masked to ensure that only voxels from the corresponding hemisphere were included (see Fig. 2.1). Finally, for each subject we extracted z-values from each of the two ROIs for the two contrasts of interest: 2nd pers. unimanual > 2nd pers. nonmanual and 3rd pers. unimanual > 3rd pers. nonmanual. We analyzed these z-values using a repeated-measures ANOVA with Hemisphere (left vs. right) and Person (2nd vs. 3rd) as within-subjects factors, and Handedness (left- vs. right-handers) as a between subjects factor.

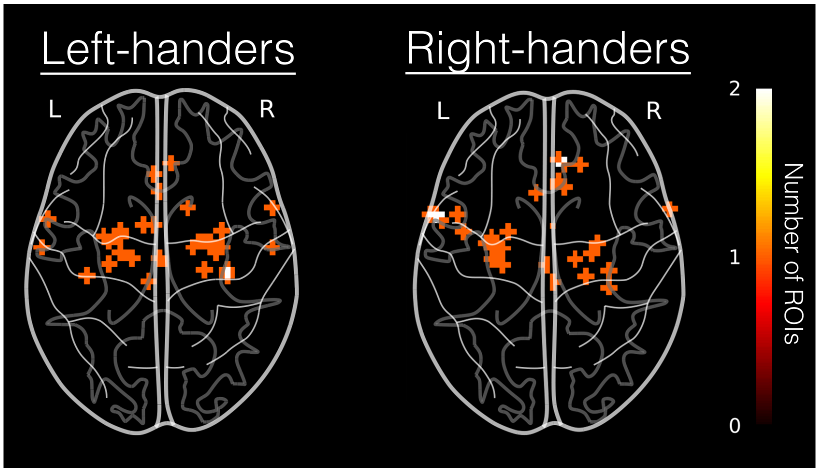

Figure 2.1: Glass-brain plot of ROIs for Unimanual > Nonmanual in left and right BA6, for left- and right-handers separately. Color values indicate number of overlapping ROIs.

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[1] By constructing our ROIs using the Unimanual > Nonmanual contrast we isolated areas selective to manual action processing. Note, that we do not interpret any main effects of Verb Type, as this would be a form of double-dipping (Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). Instead, all contrasts of interest are fully orthogonal to the contrast used for ROI definition.

2.3 Results

2.3.1 2nd-person phrases

When left- and right-handers processed 2nd-person phrases describing their own unimanual actions (vs. non-manual actions), they showed stronger activity in the BA6 ROI in the hemisphere controlling their dominant hand. Right-handers showed a stronger BOLD response in left BA6 than right BA6 (effect of Hemisphere: $F(1{,}16) = 7.38$, $p = .02$; see Fig. 2.2). Yet, when left-handers processed the same unimanual verbs, they showed the opposite pattern: stronger BOLD in right BA6 than in left BA6 (effect of Hemisphere: $F(1{,}15) = 10.92$, $p = .005$; see Fig. 2.2). The difference between left- and right-handers is supported by a significant 2-way interaction of Handedness x Hemisphere ($F(1{,}31) = 18.42$, $p < .001$), and replicates previous findings (Willems, Hagoort, & Casasanto, 2010; Willems, Toni, Hagoort, & Casasanto, 2009).

2.3.2 3rd-person phrases

Right-handers showed stronger left BA6 than right BA6 activity for both 2nd- and 3rd-person unimanual phrases (model combining 2nd- and 3rd-person verbs: effect of Hemisphere: $F(1{,}48) = 6.12$, $p = .02$; no statistically significant Hemisphere x Person interaction: $F(1{,}48) = .17$, $p = .68$; see Fig. 2.2). Left-handers, however, processed language about other people's unimanual actions in a different way from how they processed language about their own unimanual actions (significant Hemisphere x Person interaction: $F(1{,}45) = 4.29$, $p = .04$; see Fig. 2.2). Whereas for 2nd person unimanual verbs left-handers showed a stronger response in right BA6 than in left BA6, for 3rd person unimanual verbs they showed no difference in left and right BA6 activity (no statistically significant effect of Hemisphere: $F(1{,}15) = .006$, $p = .94$).

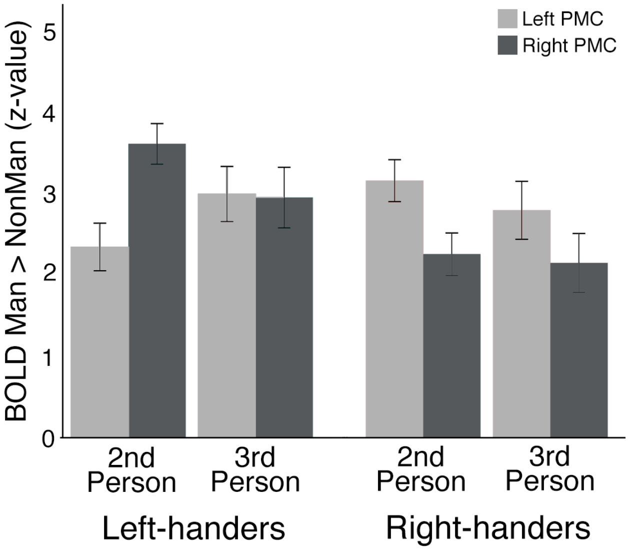

Figure 2.2: BOLD response in left and right premotor cortex (PMC) ROIs for phrases describing unimanual actions. 2nd Person = Language about own actions; e.g. *you write*; 3rd Person = Language about others' actions; e.g. *she writes.* When processing 2nd-person unimanual verbs, left- and right-handers showed a body-specific pattern of PMC activity, consistent with participants processing language about their own actions from an egocentric perspective. When processing 3rd person unimanual verbs, right-handers showed a pattern of PMC activity that did not differ from the pattern observed during processing of 2nd-person unimanual verbs. By contrast, left-handers showed a different PMC response when processing 3rd-person compared to 2nd-person unimanual verbs consistent with participants using an allocentric perspective when processing language about other people's actions.

2.3.3 Comparing 2nd- vs. 3rd-person phrases

Whereas left- and right-handers showed different patterns of activity in left vs. right BA6 when processing language about their own actions (as supported by the significant 2-way of Handedness x Hemisphere: $F(1,31) = 18.42$, $p < .001$), the groups did not show different patterns of lateralized BA6 activity for language about other people's actions (no statistically significant effect of Handedness x Hemisphere $F(1,31) = .61$, $p = .44$). The inference that left- and right-handers differ in how they understand language about their own vs. other people's actions is supported by a 3-way interaction of Handedness x Hemisphere x Person, which was marginally significant ($F(1,93) = 3.09$, $p = .08$).

2.4 Discussion

Here, we asked whether people understand language about their own actions (2nd-person phrases, e.g., *you write*) in the same way they understand language about other people's actions (3rd-person phrases, e.g., *she writes*). When processing language about their own unimanual actions, left- and right-handers showed different patterns of PMC activity, reflecting how they would perform those actions themselves: Whereas right-handers showed stronger BOLD in left PMC areas controlling the right hand, left-handers showed stronger BOLD in right PMC areas controlling the left hand. Yet, when left- and right-handers processed language about other people's unimanual actions, the patterns of PMC activity did not differ between groups. Right-handers showed the same pattern of PMC activity no matter whether they were processing language about their own actions or others' actions: Across 2nd- and 3rd-person phrases, right-handers showed stronger activity in left PMC than in right PMC hand areas. Left-handers, however, processed 2nd- and 3rd-person phrases differently: When imagining others' actions, left-handers did not show a difference in activity between left and right PMC hand areas, consistent with left-handers imagining relatively more right-handed actions. Combined, these results show that the way people understand action language depends on the specifics of their own bodies, and on whose actions are being described. Language-induced motor imagery for our own actions reflects how we use our own bodies, whereas imagery for others' actions also reflects how others use their bodies, even if their bodies differ from our own.

2.4.1 Egocentric and allocentric perspectives in action and perception

When people process language about actions, they may rely on their motor systems in two possible ways: People may imagine others' actions from an egocentric perspective (i.e. how they would perform those actions themselves) or from an allocentric perspective (i.e. how they see others perform those actions). Here, when processing language about their own actions, both groups showed a pattern of PMC activation that supports the egocentric perspective: Left-handers showed stronger BOLD in circuits controlling the left hand, whereas right-handers showed stronger BOLD in circuits controlling the right hand.

Which perspective did people take to imagine other people's actions? The data from right-handers, alone, do not allow us to distinguish between the theoretical alternatives, since both the ego- and allocentric accounts predict that right-handers should show stronger left PMC than right PMC activity (see Introduction and results from Tomasino et al., 2007). By contrast, the data from the left-handed participants provide a critical test of both accounts, since left-handers perform actions one way, but see most other people perform them differently. When left-handers processed 3rd-person phrases, their pattern of PMC activity was inconsistent with the egocentric proposal: Left-handers imagined other people's actions differently from how they imagined their own actions (as supported by the significant 2-way interaction of Person x Hemisphere).

Although the 3rd-person data rule out the egocentric proposal, left-handers did not show the pattern of PMC activity most clearly predicted on the allocentric account, namely stronger BOLD in left PMC than in right PMC. Nonetheless, the qualitative changes in PMC activity driving the critical 2-way interaction of Person x Hemisphere suggest that left-handers relied on an allocentric perspective to imagine others' actions, for two reasons. First, when left-handers processed 3rd-person phrases, they showed decreased BOLD in right PMC circuits controlling the left hand and increased BOLD in left PMC circuits controlling the right hand, compared to when they processed 2nd-person phrases (see Fig. 2.2). This pattern is consistent with left-handers imagining relatively fewer left-handed actions and more right-handed actions, thereby supporting the allocentric account.

Second, even if left-handers predominantly imagined others' actions as being right-handed, left-handers may still have partially used the right PMC motor systems they would use to perform those actions. On the basis of studies of interhemispheric transfer (Wiestler, Waters-Metenier, & Diedrichsen, 2014), participants may have relied on their own experience of performing left-hand actions to help them imagine other people's right-hand actions. That is, left PMC activity may have reflected people's imagery based on their history of visually perceiving right-hand actions, whereas right PMC activity may have reflected their history of performing left-hand actions, and the use of these left-hand motor programs to structure right-hand imagery (see Wiestler et al., 2014, for analogous effects when people are trained to perform a task with one hand and afterwards perform the same task with the other, untrained hand). On another, non-mutually exclusive possibility, left-handers may have imagined most of the actions from an allocentric perspective, but may have relied on an egocentric perspective for some actions, even when presented with 3rd-person phrases, when it was difficult to imagine performing the action with the right hand (e.g. people may find it easier to imagine using their nondominant hand for an action like *scratching* than an action like *writing*). Overall, the left-handers' results imply that people often imagine other people's actions from an allocentric perspective, based on the way they see others performing these actions; constructing this allocentric representation, however, may rely partly on the motor circuits people use for performing the actions, themselves.

2.4.2 Motor imagery: specific to whose body?

According to the body-specificity hypothesis (BSH), "To the extent that the content of the mind depends on the structure of the body, people with different kinds of bodies should tend to think differently, in predictable ways," (Casasanto, 2011, p. 378; Casasanto, 2009). Here, we tested the BSH by asking how people process language about their own unimanual actions (2nd-person phrases). The results offered clear support for the BSH: Left- and right-handers, who perform the same unimanual actions in different ways also imagine those actions in correspondingly different ways, thereby replicating and extending previous findings (Willems et al., 2009; Willems, Hagoort, & Casasanto, 2010).

In contrast to the 2nd-person condition, the 3rd-person condition was designed, not to ask *whether* motor imagery of others' actions is body-specific, but to ask *whose body* this type of imagery is specific to. Regardless of whether people were to take an egocentric or an allocentric perspective to imagine others' actions, their imagery would still be based on the specifics of someone's body, even though that body may not be their own. In principle, participants could have taken either perspective (e.g. they could have imagined other people's actions in a way that reflects their own bodies, casting themselves in the role of the "he" or "she" described in the phrase). Yet, our data suggest that they imagined 3rd-person actions by taking a perspective specific to the other person's body. This allocentric pattern is consistent with the findings of previous studies on body-specific judgments of emotional valence: When participants were instructed to take another person's perspective, their valence judgments reflected the specifics of the other person's body (Kominsky & Casasanto, 2013; de la Fuente, Casasanto, & Santiago, 2015; de la Fuente, Casasanto, Martínez-Cascales, & Santiago, 2017). The present results show that people also take an allocentric perspective when processing language about others' actions, and that they do so even when they're not explicitly instructed to take this perspective. Together, these studies support the BSH, and extend it by showing that people's neuro-cognitive representations can flexibly reflect the specifics of different types of bodies, depending on the contextual demands.

2.4.3 Different types of experience shape action language understanding

Most theories of embodied cognition agree that action experience shapes the way people process action language. Yet, different researchers have made contrasting assumptions about the kinds of experience that shape these processes. On one proposal, people understand action language by relying on the same motor circuits they use to perform those actions. On this view, people process action language "as if [they] were preparing for situated action," (Barsalou, 2005, p. 642), and their understanding of action words "refer[s] to movements of one's own body," (Pulvermüller, 1999, p. 261). If this proposal is correct, then the way in which people process action language should be shaped primarily by their motor experience of performing those actions. On a second proposal, people understand action language by relying on the same motor circuits they use to perceive those actions being performed by others: "Words generate internal simulations of actions that are more similar to watching others act than to acting oneself," (Rueschemeyer, Ekman, van Ackeren, & Kilner, 2014, p. 1650). If this proposal is correct, then people should process action language in a way that reflects their visual experience of perceiving actions, rather than their motor experience of performing actions.

Previous studies could not distinguish between the motor experience and the visual experience accounts, because they tested participants who typically perform and perceive actions in the same way (Tomasino et al., 2007; Hartung, Hagoort, & Willems, 2017; Rueschemeyer et al., 2014). Here, we show that the way in which people understand action language is based on their motor experience of performing actions in some contexts, and also on their visual experience of perceiving actions in other contexts, depending on which kind of experience is most relevant for understanding the phrases describing these actions. When people understand language describing actions they would perform themselves, they show PMC activity that reflects their own motor experience: Right-handers imagine right-hand actions, whereas left-handers imagine left-hand actions. Yet, when people understand language describing actions they would see other people perform, their PMC activity also reflects their visual experience of others performing those actions. Since both left- and right-handers typically see people perform unimanual actions using the right hand, they imagine other people's actions as being right-handed. As such, people appear to process action language by relying on different types of experience – motor experience or visual experience – depending on which experience matters most for constructing meaning.

2.4.4 Deep vs. shallow tests of language understanding

In this study, we tested how motor systems contribute to action language understanding by using a language-induced imagery task. Mental imagery is one common way in which people perform tasks that require deep semantic or conceptual processing (Moulton & Kosslyn, 2009). For instance, people may rely on imagery when they verify the properties of objects (e.g. "Do roses have thorns?"; Kan, Barsalou, Olseth Solomon, Minor, & Thompson-Schill, 2003) or when they process detailed narratives (Hartung et al., 2017).

Yet, even though people may rely on imagery to construct detailed semantic representations, they may rely on different processes in contexts where more shallow processing of meaning suffices. For instance, during regular conversations people may construct meaning by relying on modality-specific *simulation*, a process that is functionally and neurally separable from imagery. In contrast to imagery, which constitutes a detailed re-enactment of past experiences, simulations may be pre-enactment: Simulations prepare people for future interactions by pre-activating the relevant perceptuo-motor circuits (Willems, Toni, Hagoort, & Casasanto, 2010). fMRI evidence supports this functional distinction: When people process language about actions with no actor specified, both simulations and imagery lead to body-specific PMC activation (Willems, Hagoort, & Casasanto, 2010; Willems et al., 2009), yet simulations have been shown to rely on circuits for motor planning that are distinct from the motor circuits activated by imagery (Willems, Toni, et al., 2010). Therefore, whereas our results show that people process language about others' actions from an allocentric perspective when using imagery, they do not rule out the possibility that people may adopt a different perspective when processing linguistic meaning more shallowly.

2.5 Conclusions

Here, we found that the same action verbs cue motor-system activity in different cerebral hemispheres depending on the perspective implied by the verb form and the bodily characteristics of the language user. When people processed language about their own unimanual actions, they showed PMC activity consistent with them imagining these actions from an egocentric, body-specific perspective: Right-handers imagined right-hand actions, whereas left-handers imagined left-hand actions. Yet, when people processed language about other people's unimanual actions, they showed PMC activity consistent with them understanding these actions from an allocentric perspective: Both left- and right-handers imagined unimanual actions in the same way. Our data show that people understand language about the same actions in different ways, both within and across individuals: Language-users flexibly combine different sources of experience to build meaning, depending on who is performing the actions and how the linguistic agents typically use their bodies to perform those actions.

CHAPTER 3

TDCS TO PREMOTOR CORTEX CHANGES ACTION VERB UNDERSTANDING: COMPLEMENTARY EFFECTS OF INHIBITORY AND EXCITATORY STIMULATION

3.1 Introduction

According to theories of embodied cognition, word meaning relies, in part, on neural systems for perceiving and acting (Barsalou, 1999). Support for this proposal comes from neuroimaging studies of action language understanding. When people read action verbs like kick, pick, and lick, motor areas show somatotopic activation (i.e. kick, pick and lick preferentially activate leg-, hand-, and mouth-areas, respectively; Hauk et al., 2004; see Pulvermüller, 2005, for review).

What is the motor system contributing to action verb understanding? On one view, motor simulations recapitulate previous action experiences by re-activating some of the neural circuits used to perform those actions (Barsalou, 1999; Pulvermüller, 2005). According to this re-enactment account, Hebbian learning creates connections between neural circuits involved in action execution (most critically primary motor cortex; M1), and neural representations of the action verb word forms (Pulvermüller, 2005). On an alternative view, motor simulations may partially prepare the motor system for future actions – thus, simulations are "pre-enactments" rather than reenactments (Willems, Toni, et al., 2010; Zwaan & Kaschak, 2008). If the pre-enactment view is correct, motor simulations should be implemented primarily in neural systems that support action planning, instead of action execution. fMRI data support this proposal: processing action verbs correlates mainly with activity in motor planning areas (e.g., premotor cortex; PMC), rather than activity in motor execution areas (e.g., primary motor cortex; Willems, Toni, et al., 2010; Aziz-Zadeh et al., 2006; Tettamanti et al., 2005; but see Pulvermüller, 2005).

To date, only one study tested the functional role of PMC in action verb understanding. Willems and colleagues used continuous theta-burst stimulation (cTBS) to perturb activity in either left or right PMC areas involved in planning right- and left-hand actions, respectively. Right-handed participants then made lexical decisions on unimanual and nonmanual action verbs. They responded faster to unimanual action verbs after cTBS to left PMC than after cTBS to right PMC. By contrast, cTBS to left vs. right PMC did not differentially affect responses to nonmanual action verbs (Willems et al., 2011). fMRI evidence suggests that these effects were likely driven by cTBS to dominant hand areas in left PMC: When right-handers processed unimanual action verbs in the scanner, they showed BOLD modulation in right-hand areas in left PMC, but not in left-hand areas in right PMC (Willems, Hagoort, & Casasanto, 2010).

Yet, the direction of Willems et al.'s reaction time pattern was unexpected. cTBS has been shown to suppress neural excitability(Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005). On the simplest prediction, left PMC stimulation might be expected to impair, instead of improve, performance. Therefore, Willems et al.'s data may be an instance of "paradoxical functional facilitation,"(Kapur, 1996): Patients with brain lesions to inhibitory circuits sometimes show enhanced behavioral performance, relative to controls (Kapur, 1996; Papeo, Pascual-Leone, & Caramazza, 2013). Likewise, cTBS to left PMC might have facilitated action verb processing by modulating inhibitory PMC circuits (Prut & Fetz, 1999; Sawaguchi, Yamane, & Kubota, 1996; Kroeger et al., 2010; Duque, Labruna, Verset, Olivier, & Ivry, 2012). On one possibility, inhibition may prevent people from overtly performing the actions named by verbs, rather than covertly simulating them. For instance, when people read a verb like "kick", inhibition may be necessary to stop people from performing an actual kicking movement (except, of course, if this action is contextually appropriate; Willems et al., 2011). This post-hoc explanation generates testable predictions regarding the effects of inhibitory vs. excitatory stimulation of left PMC: Whereas inhibitory stimulation to left PMC should improve performance on action verbs, excitatory stimulation of the same region should impair performance.

Here we used transcranial Direct Current Stimulation (tDCS) to test for complementary effects of excitatory and inhibitory left PMC stimulation on action verb understanding. tDCS passes a weak direct current between two scalp electrodes, increasing neural excitability under the anodal electrode and decreasing excitability under the cathodal electrode (Nitsche et al., 2008; Jacobson, Koslowsky, & Lavidor, 2012). Right-handers received tDCS over hand areas in left and right PMC, with the left-right configuration of the anode and cathode counterbalanced across participants. Following stimulation, participants performed a lexical decision task involving unimanual and abstract verbs, responding with their left and right hands.

We expected that inhibitory, cathodal stimulation over left PMC hand area would cause an improvement in processing unimanual action verbs, as found by Willems et al. By contrast, excitatory, anodal stimulation to the same area was expected to cause an impairment in processing unimanual action verbs, thereby complementing the pattern found by Willems et al.

3.2 Methods

3.2.1 Participants

73 participants from the University of Chicago community took part in the experiment. Data from 1 participant who did not follow the task instructions were replaced, and data from 1 other participant were lost due to a script error. The remaining 71 participants (33 females, 38 males) were monolingual native English speakers and were right-handed as established by the Edinburgh Handedness Inventory (EHI: M = 78; range = 47–100; Oldfield, 1971). Participants were healthy adults who did not report being pregnant, having sustained a stroke or brain injury, being on psychoactive medication, or having any electronic implants. All participants provided informed consent and received course credit or \$30 for

their participation. All procedures were in accordance with the guidelines approved by the Institutional Review Board of the University of Chicago.

3.2.2 Materials and Procedure

Stimuli

198 verbs were used in this experiment: 66 unimanual verbs (e.g. to write), 66 abstract verbs (e.g. to tempt), and 66 phonotactically legal nonce words (e.g. to frinckle). Unimanual action verbs were selected based on the results of a pantomime rating study. In the pantomime study, 10 participants read each of the unimanual action verbs used by Willems et al. (2011) and acted out the actions described by them. All participants had a strong hand preference, as established by the Edinburgh Handedness Inventory (8 strong right-handers: EHI: $M = 92$; range = 70-100; 2 strong left-handers: EHI: $M = -100$, range = -100). For each pantomime, we coded which hand participants used to perform the action. Our final stimulus set only included those verbs that elicited primarily dominant hand responses (lower bound cut-off set at 60% dominant hand responses; total N of final stimulus set = 66; proportion dominant hand responses: $M = 90\%$; range = 60-100%).

Although we used a within-item design, all three verb types were matched in word length (unimanual vs. abstract: $t(130) = 1.48$, $p = .14$; unimanual vs. nonce: $t(130) = -.74$, $p = .46$; abstract vs. nonce: $t(130) = -.74$, $p = .46$). Unimanual and abstract verbs were matched in word frequency ($t(96) = .20$; $p = .85$; Coltheart, 1981).

Transcranial Direct Current Stimulation

tDCS was performed using a battery-powered Soterix Medical 1x1 (Soterix Medical, New York) with two 5x7cm saline-soaked sponges covering the electrodes. Each participant received 20 minutes of stimulation at 2 mA, which was slowly ramped up from 0 mA at stimulation onset, and ramped down to 0 mA at stimulation offset. Both ramping up and ramping down happened over the course of 20 seconds. The electrodes were placed over premotor hand areas, at FC3 and FC4 in the 10-20 electrode system (Nitsche et al., 2008; Koessler et al., 2009). We selected FC3 and FC4 because these electrodes provided the closest overlap with the MNI coordinates of PMC hand areas (MNI coordinates were based on fMRI data from Willems, Hagoort, & Casasanto, 2010; MNI to electrode mapping was based on the conversion table provided by Koessler et al., 2009).

In the left PMC inhibition condition (N=35), the cathode was placed at FC3 and the anode at FC4, inhibiting left PMC and simultaneously exciting right PMC. In the left PMC excitation condition (N=36) this placement was reversed, with the anode placed at FC3 and the cathode at FC4, exciting left PMC and inhibiting right PMC. All participants tolerated stimulation; one participant expressed discomfort. During stimulation, participants did not perform any task and were asked to refrain from moving. We selected this approach, first, because performing motor actions during tDCS can change the effects of tDCS, and second, because the effects of tDCS persist up to an hour after stimulation (see Nitsche et al., 2008).

Behavioral Procedure

After receiving tDCS participants performed a lexical decision task. Verbs appeared one at a time in the center of a computer screen. Participants indicated whether each stimulus was an existing English word by pressing a button corresponding to “yes” or “no” with their left or right index finger. The response mappings for each button were presented below the verb, on the left or right side of the screen. For each verb type, the “yes” response was mapped to the right button for half of the stimuli and to the left button for the other half (mapping counterbalanced across participants). The stimuli appeared in a random order, and the placement of the response labels varied unpredictably from one trial to the next.

Every trial had the following structure (see Figure 3.1). First, participants saw a “Ready?” sign prompting them to push and hold down the two white “home” buttons with their left and right index finger (mapped to the ‘d’ and ‘k’ keys). Once the buttons were held down, a fixation cross appeared for a duration randomly selected between 750 and 1250 *ms*. Then, the stimulus and response prompts appeared. As soon as the participant had decided the correct response, they released the home button held down by the response hand and used the same hand to push the correct pink response button, after which a new trial started. Response buttons were mapped to the 'z' and 'period' keys. If participants released either of the home buttons before the stimulus was presented, the trial was restarted. If participants released or pressed the wrong buttons in response to the stimulus, they received feedback and the response was classified as incorrect.

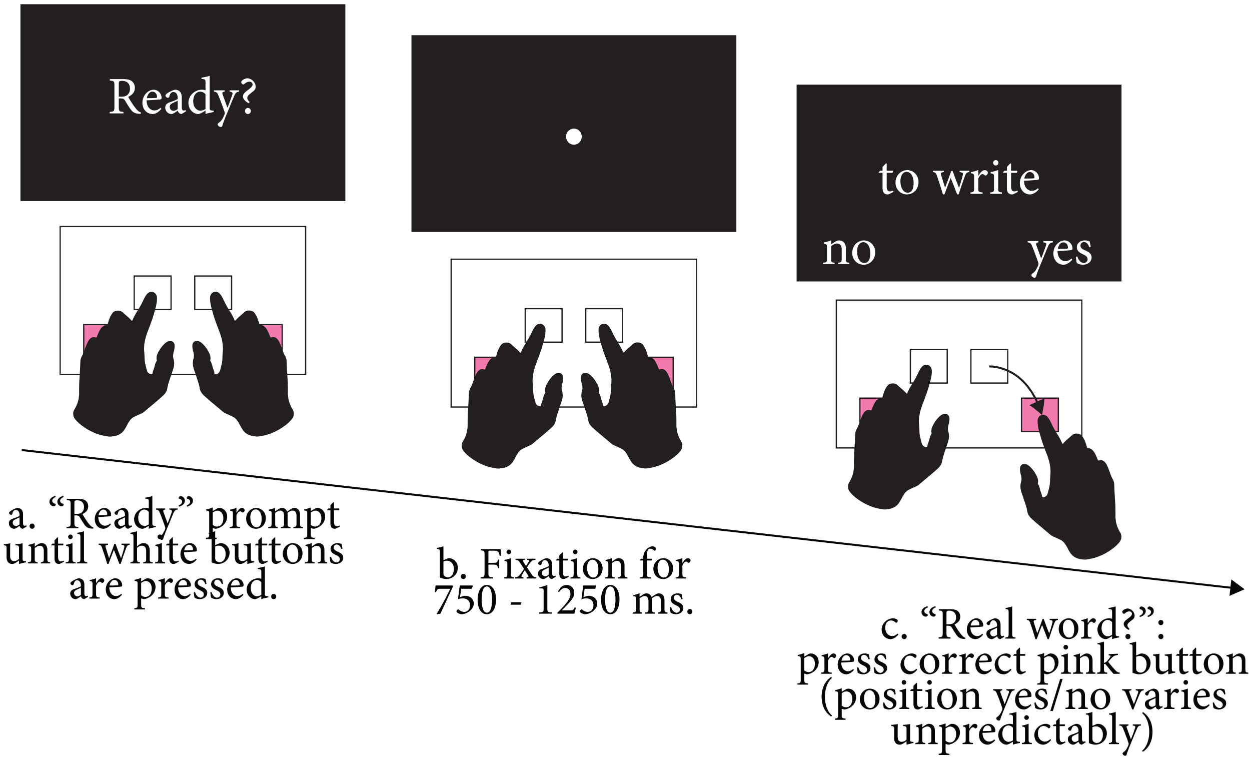

Figure 3.1: Typical lexical decision trial.(a)"Ready?" prompt until participants pressed and held down the two white buttons. (b) Fixation for a random duration between 750–1250 ms. Participants kept holding down the white buttons. (c) The stimulus and response labels appeared, participants formulated their response and pressed the pink button corresponding to the correct response.

Data Analysis

The accuracy data and RTs for target trials were analyzed with mixed effects models using the 'lme4' package (Bates, Mächler, Bolker, & Walker, 2014) for R (R Core Team, 2019). The independent variables for both models consisted of three two-level fixed effects: tDCS polarity (left inhibitory vs. left excitatory); verb type (unimanual vs. abstract), and response hand for the required response (left vs. right). We included random effects for participant and word, and used the maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013). Nonce trials were excluded before the analyses. Accuracy data were analyzed using a general linear model with a binomial linking function. The dependent variable for this model was whether the response for each trial was correct or incorrect. For the RT model, we discarded all the incorrect trials and log-transformed RTs to reduce skew in the residuals.

Both the accuracy and RT models used the following formula: DV (Accuracy/RT) $\sim$ tDCS Polarity x Verb Type x Response Hand + (1 + Verb Type x Response Hand — Participant) + (1 + tDCS Polarity x Response Hand — Word).

Finally, to test the constituent interactions of the 3-way interactions, we used separate models to test for lower-order interactions for each verb type (e.g. the 2-way interaction of tDCS Polarity x Response Hand for unimanual action verbs and abstract verbs). These models had the exact same fixed and random effect structure as the full, higher-order model, except that they did not include the factor Verb Type. Outputs for each model are included in the Supplementary Material.

3.3 Results

3.3.1 Accuracy

Thee polarity of tDCS to left PMC differentially affected the accuracy of participants' responses to unimanual vs. abstract verbs, as indicated by a significant 3-way interaction of tDCS polarity x Verb type x Response hand (β = 0.82, *SE* = 0.40, z = 2.07, p = 0.04;

Figure 3.2a). In addition to the predicted 3-way interaction, we also found the predicted qualitative pattern of results for the constituent 2-way interactions. This qualitative pattern showed that inhibitory left PMC stimulation tended to cause a relative improvement in performance for right-hand responses, whereas excitatory left PMC stimulation tended to cause a relative impairment; by contrast, tDCS polarity had no systematic effect on accuracy for abstract verbs. This pattern suggests that the predicted relationship between tDCS polarity and response hand was selective for unimanual verbs, yet the 2-way interaction needed to confirm this inference showed the predicted pattern, qualitatively, but was not statistically significant ($\beta = 0.32$, $SE = 0.32$, $z = 0.98$, $p = 0.33$).

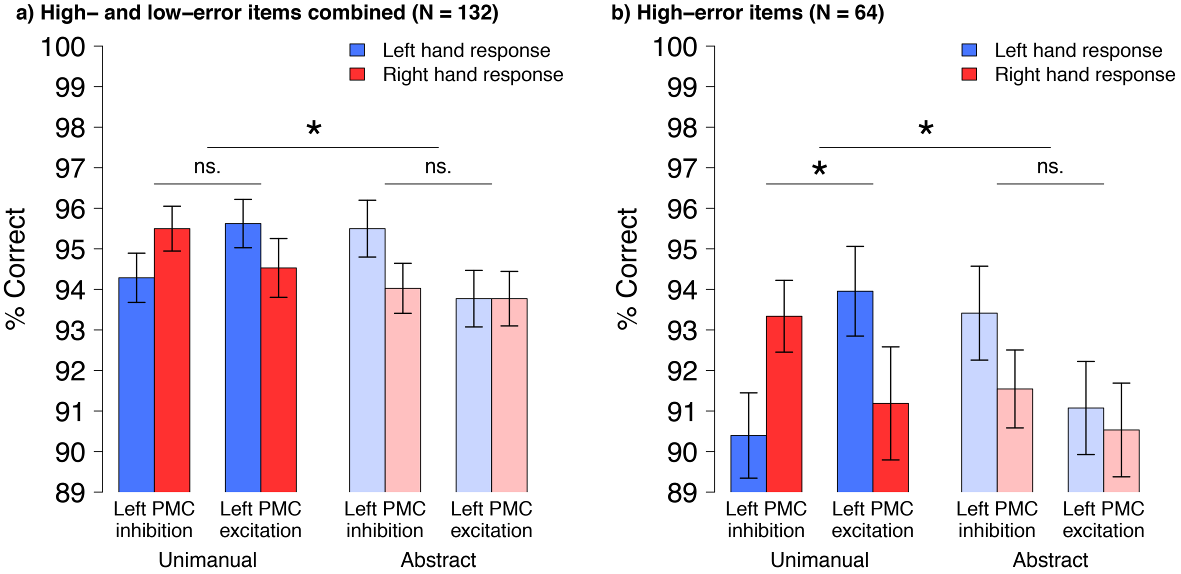

Figure 3.2: Mean accuracy on the lexical decision task for (a) all items and (b) items with a high error rate. Left PMC Inhibition = cathode left PMC, anode right PMC; Left PMC Excitation = anode left PMC, cathode right PMC. Unimanual and Abstract refer to the Verb type of the stimuli. Error bars reflect within- subject SEM. *Indicates $p < 0.05$.

One possible reason why the predicted 2-way interaction in the unimanual verb condition did not reach significance is that accuracy approached 100%, in all conditions: a ceiling effect. To determine whether the predicted effects were masked by this ceiling effect, we performed a second analysis on a subset of items that were not near ceiling. We calculated the number of errors for each verb (Range = 0 - 16 errors, *Median* = 3) and then performed a median split to identify items that led to more errors (High-error items: n = 31 unimanual verbs, n = 33 abstract verbs; Low-error items: n = 35 unimanual verbs, n = 33 abstract verbs).

The accuracy analysis of high-error items again showed the predicted 3-way interaction of tDCS polarity x Verb type x Response hand (β = -1.07, *SE* = .47, z = -2.29, p = .02; Figure 3.2b). As expected, this 3-way interaction was driven selectively by responses to unimanual verbs, as shown by a significant 2-way interaction of tDCS polarity x Response hand (β = .80, *SE* = .35, z = -2.32, p = .02; Figure 3.2b). After inhibitory stimulation to left PMC, participants tended to respond more accurately to unimanual verbs with their right hand than with their left hand (β = -.41, *SE* = .26, z = -1.58, p = .11). After excitatory stimulation to left PMC, we found a trend in the opposite direction: participants tended to respond less accurately with their right hand than with their left hand (β = .62, *SE* = .37, z = 1.67, p = .10). As expected, there was no statistically significant 2-way interaction of tDCS polarity and Response hand for abstract verbs (β = .20, *SE* = .36, z = .56, p = .58).

Although not of interest, for completeness we report that analysis of the low-error (near-ceiling) items showed no evidence for a 3-way interaction of tDCS polarity x Verb type x Response hand (β = -.18, *SE* = .74, z = -.25, p = .80) nor for either of the 2-way interactions of tDCS polarity x Response hand (unimanual verbs: β =.08, *SE* = 0.68, z = .11, p = 0.91; abstract verbs: β =.43, *SE* = 0.65, z = .66, p = 0.51).

3.3.2 Reaction Times

RTs were defined as the latency from stimulus onset to release of the “home” button. There were no statistically significant effects for the 3-way interaction of tDCS polarity x Verb type x Response hand (Wald χ^2 (1) = .68, p = .41), nor for the constituent 2-way interactions of tDCS polarity x Response hand for either verb type (unimanual: Wald $\chi^2(1)$ = .10, p = .75; abstract: Wald $\chi^2(1)$ = .31, p = .58; see Figure 3.3). As with the accuracy data, we analyzed the release RTs separately for the high- and low-error items. There were no statistically significant 3-way or 2-way interactions in either model (all Wald χ^2s $<$ 1.94;

all $ps > .15$). The lack of any RT effect argues against a speed-accuracy trade-off as an explanation for our observed accuracy effects.

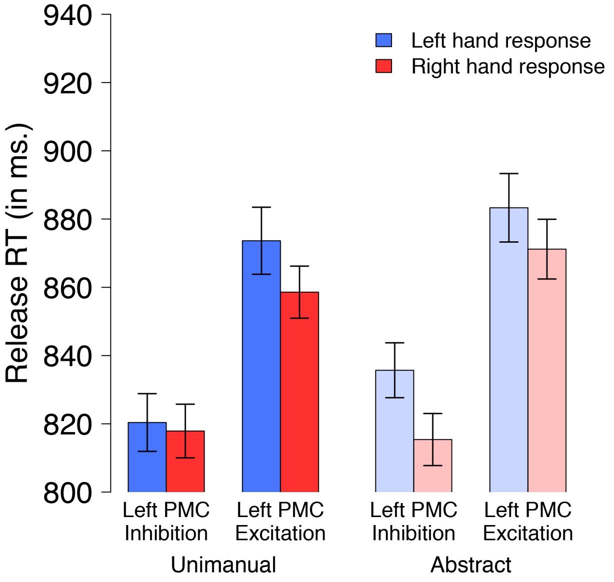

Figure 3.3: Mean release reaction time on the lexical decision task for all items. Left PMC Inhibition = cathode left PMC, anode right PMC; Left PMC Excitation = anode left PMC, cathode right PMC. Unimanual and Abstract refer to the Verb type of the stimuli.

3.4 Discussion

This study tested whether motor circuits involved in action preparation play a causal role in action verb understanding. To this end, we used two tDCS configurations to alter the state of excitability in hand areas of premotor regions. For one configuration, the anodal electrode was positioned over the left PMC and the cathodal electrode over the right PMC, a configuration assumed to enhance excitability in left PMC. For the other configuration, the electrodes were reversed to reduce excitability (or promote an inhibitory state) in left PMC. Inhibitory and excitatory tDCS to left PMC differentially affected the accuracy of responses to unimanual action verbs, but not to abstract verbs. After left PMC inhibition, right-handers tended to make fewer errors to unimanual verbs with their right hand than with their left hand. After left PMC excitation, right-handers tended to make more errors to unimanual verbs with their right hand than with their left hand. By contrast, the configuration of tDCS did not differentially influence how accurately participants responded to abstract verbs. These results demonstrate complementary effects of exciting and inhibiting left PMC activity on action verb processing.

Neurostimulation to motor areas has been shown to benefit action language processing, but previous studies have provided "no evidence yet that sensory-motor cortex stimulation disrupts [i.e., impairs] semantic processing," (Hauk & Tschentscher, 2013, p. 6; see also Mahon & Caramazza, 2005, 2008). Here, depending on the configuration of tDCS and on the response hand, we found both a relative improvement and a relative impairment in accuracy for lexical decisions, using a task known to produce semantic priming effects (Neely, Keefe, & Ross, 1989). If we assume that tDCS-induced inhibition is similar to disruption caused by cTBS, then the current results are similar to those reported by Willems et al. (2011): Both conditions produced "paradoxical facilitation" of lexical decision after inhibition or disruption of left PMC hand areas. Conversely, we showed "paradoxical impairment" after excitation of the same area. One explanation for the complementary effects of excitatory and inhibitory neurostimulation builds on the idea that there is competition between different possible simulations of the same action. For instance, given the verb "throw," people could simulate either an overhand or an underhand throw. Perhaps both of these simulations are partially activated initially, but since these actions cannot be performed simultaneously, the developing simulations compete and one "wins." Left-inhibitory stimulation could facilitate performance by reducing activation of competing simulations, whereas left-excitatory stimulation may impair performance by increasing this competition (see Willems et al., 2011; Prut & Fetz, 1999; Sawaguchi et al., 1996; Kroeger et al., 2010; Duque et al., 2012).

An alternative explanation of these complementary effects of tDCS is based on the idea that inhibition of modality-specific areas may minimize the conflict between simulations and task-relevant perceptual or motor processes. Analogous to our results in the motor modality, Landau and colleagues (Landau, Aziz-Zadeh, & Ivry, 2010; see also Aziz-Zadeh et al., 2008) found that after people process language about faces, they show impaired (rather than improved) behavioral and neural responses to pictures of faces. In both Landau et al.'s study and our own, words may have cued activity in the relevant perceptuo-motor systems, but this activity needed to be inhibited because the task did not call for the corresponding percepts or actions (e.g., given the verb "throw," our participants were not expected to throw, but rather to press a button). On this account, PMC inhibition may help ensure that simulations do not result in the overt execution of the action named by a verb. Left-inhibitory stimulation may have improved behavioral performance by increasing inhibition of situationally inappropriate motor plans. Left-excitatory stimulation may have impaired performance by boosting activation of all potentially relevant motor plans (i.e., both the verb-cued simulations and preparations for the manual response), thus increasing competition among these representations. Further experiments are needed to test these potential explanations, and to determine the mechanisms underlying the paradoxical improvement and impairment effects we observed.

The current data also provide evidence that motor system activity affects how well people process action verbs. Previous neurostimulation results showed that changing activity in the motor system affects the speed with which people process action verbs (Willems et al., 2011; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005). Yet, as Willems and Casasanto point out, these data do not address how motor activity changes the quality with which people understand these verbs (Willems & Casasanto, 2011). Here we show that stimulation of hand areas affects how accurately participants process manual action verbs. In combination with previous findings, these results suggest that motor simulations contribute to both how fast and how well people construct the meaning of action language.

Why did we observe the predicted pattern in the accuracy data but not in the RT data? Since we did not speed participants (e.g., with a trial timeout), it may not be surprising that we observed the predicted interactions in the accuracy data, alone. Furthermore, the absence of an RT effect allows us to rule out the presence of a speed-accuracy trade-off. In general, it is often unclear a priori whether studies investigating motor-system contributions to action language understanding will show the predicted effect in RTs, accuracy, or both (see Mahon & Caramazza, 2008). Across our cTBS and tDCS studies, we find the predicted effects in both reaction times and accuracy. Since finding the predicted effect in either accuracy or RT could be interpreted as support for our experimental hypothesis, a reasonable (though non-standard) precaution to take would be to double our p-values (i.e. Bonferroni correction). Even if we do so, the critical 3-way and 2-way interactions remain significant in our high-error data set.

We observed the predicted 3-way interaction of tDCS polarity, verb type, and response hand in the full data set, but the predicted 2-way interaction of tDCS polarity x response hand was not significant, presumably due to a ceiling effect. Overall, these results should be interpreted with some caution given that we had to perform an unplanned median split in order to observe the predicted 2-way interaction of tDCS polarity by response hand. Our confidence in the data is increased, however, by the facts that (a) the critical 3-way interaction was significant in all analyses, (b) inhibitory left PMC stimulation produced a close conceptual replication of our previous cTBS study, and (c) excitatory left PMC stimulation produced the predicted mirror image of these results, providing further convergent evidence that left PMC activity plays a functional role in processing unimanual action verbs.

In this study, we targeted PMC, rather than primary motor cortex (M1), because we hypothesize that PMC is associated with implicit simulations underlying language processing, whereas M1 is involved in overt action execution and explicit motor imagery: a hypothesis supported by previous fMRI data (Willems, Toni, et al., 2010; Willems, Hagoort, & Casasanto, 2010). Studies reporting a functional role of M1 in action language processing often rely on tasks that encourage participants to use imagery. In one study (Niccolai, Klepp, Indefrey, Schnitzler, & Biermann-Ruben, 2017), participants received tDCS to M1 hand areas while they made concreteness judgments on hand- and leg-action verbs, a task which requires deep semantic processing and is conducive to imagery. The results showed that cathodal tDCS made participants faster to judge the concreteness of action verbs (compatible with the current results) but also showed that this RT improvement was restricted to those participants who were doing the deepest semantic processing, and who were therefore the most likely to rely on explicit imagery (Niccolai et al., 2017). Previous studies that stimulated M1 to test its functional role in action language processing have produced somewhat inconsistent findings (Pulvermüller et al., 2005; Liuzzi et al., 2010; Vicario & Rumiati, 2012; Papeo, Vallesi, Isaja, & Rumiati, 2009; Tomasino, Fink, Sparing, Dafotakis, & Weiss, 2008; Gerfo et al., 2008). Whether or not M1 stimulation affects action verb processing may depend, in part, on whether the tasks encourage participants to explicitly imagine motor actions (which appears to depend on M1 as well as PMC), or only to implicitly simulate them (which appears to depend primarily on PMC, rather than M1; Willems, Toni, et al., 2010; Willems, Hagoort, & Casasanto, 2010).

The pattern of results described above is compatible with the proposal that implicit simulations during lexical decision constitute partial preparation for the actions named by the verbs, and should therefore rely more on action planning areas (PMC) than on areas directly involved in action execution (M1). Yet, the low spatial resolution of tDCS leaves open the possibility that the current spread to nearby cortical regions, including ipsilateral hand areas in M1. Nonetheless, several factors make it likely that our results are driven by stimulation of PMC rather than M1. First, the tDCS montage was specifically set up to target PMC: We determined the appropriate electrode positions for targeting PMC hand-areas using MNI coordinates from previous fMRI work (Willems, Hagoort, & Casasanto, 2010) and using MNI-to-electrode positioning conversion tables (Koessler et al., 2009). As the current density is the highest under the focal point of stimulation (Wagner et al., 2007), PMC hand areas were receiving the most focal stimulation. Second, the literature on action language processing provides both theoretical and empirical motivation for the idea that shallow language processing tasks (like lexical decision) rely on PMC and not M1. Still, we cannot definitively rule out the possibility that M1 was also affected by our tDCS stimulation.

If M1 stimulation contributed to the present results this would call for a modification of our arguments about the neural bases of explicit imagery vs. implicit simulation (since M1 is implicated more strongly in the former than the latter), but the other theoretical inferences we are making from these data would remain unchanged.

Finally, although our tDCS montage was designed to target left PMC, we also simultaneously stimulated right PMC. Could the current pattern of results be explained by inhibitory or excitatory stimulation to right PMC, alone? Based on the results from previous studies, the answer appears to be: No. When right-handed participants process unimanual action verbs, they primarily rely on left PMC hand circuits, but not on right PMC hand circuits. This pattern is now supported by two fMRI studies (Willems, Toni, et al., 2010; Willems, Hagoort, & Casasanto, 2010), and one cTBS study (Willems et al., 2011). This lateralized pattern of activity is consistent with the proposal that right-handers understand language about unimanual actions by relying on the same circuits they typically use to perform those actions: left PMC circuits that control the right hand. Nonetheless, even though stimulation of right PMC alone cannot fully account for the present results, changes in right PMC activity could have strengthened the observed pattern. Because left and right PMC are connected through transcallosal pathways, stimulation of right PMC could have affected activity in left PMC through interhemispheric inhibition (Daskalakis, Christensen, Fitzgerald, Roshan, & Chen, 2002; Bestmann et al., 2007), which may have increased the inhibitory effects of ongoing cathodal stimulation to left PMC. Yet, even if interhemispheric inhibition played a role in strengthening our results, this mechanism does not change the inference that left PMC plays a functional role in understanding manual action language, and that stimulating left PMC produces the observed paradoxical effects.

3.5 Conclusions

To conclude, these results point to a functional relationship between neural systems for planning hand actions and for understanding language about those actions. tDCS to PMC affected how accurately people processed action language: A configuration that induced inhibition of left PMC caused a relative improvement in performance (consistent with our previous cTBS results), whereas a configuration that induced excitation of left PMC caused a relative impairment. These complementary effects of excitatory and inhibitory tDCS were specific to unimanual action verbs, and depended critically on the hand that participants used to respond. Previous neurostimulation results have shown that modulating PMC activity can influence how fast people respond to action verbs. The present results show that modulating PMC activity in the hemisphere that controls the dominant hand can also affect how well people process verbs that name dominant-hand actions, strengthening the evidence that motor simulations contribute to the meanings of action words.

CHAPTER 4

HAND USE NORMS FOR DUTCH AND ENGLISH MANUAL ACTION VERBS: IMPLICIT MEASURES FROM A PANTOMIME TASK.

4.1 Introduction

How do people understand the meaning of words? According to theories of embodied cognition, people construct linguistic meaning by relying, in part, on neural systems for action and perception (Barsalou, 1999; Pulvermüller, 1999). So far, the most fruitful testbed for these theories has been the neural representation of action verb semantics: When people process action language, they show somato-topic patterns of activity in (pre)motor cortex (e.g. when processing verbs like "kick", "pick", and "lick", people show activity in motor areas controlling the leg, hand, and mouth; Hauk et al., 2004; Aziz-Zadeh et al., 2006).

Unimanual action verbs have offered particular theoretical leverage for testing embodiment claims, because of the hemispheric specialization of the motor systems controlling the hands: Whereas left hemisphere motor circuits control the right hand, right hemisphere motor circuits control the left hand. By relying on this organizational principle of the neural systems for manual control, Willems and colleagues (2010) were able to use unimanual action verbs to show that left- and right-handers, who perform the same manual actions in different ways, also process language about those actions in correspondingly different ways. When reading unimanual action verbs, right-handers showed stronger activity in left premotor cortex areas controlling the right hand, whereas left-handers showed relatively increased activity in right premotor cortex controlling the left hand (Willems, Hagoort, & Casasanto, 2010; see also Casasanto, 2009, 2011). Other studies have used unimanual action verbs to demonstrate that premotor circuits play a functional role in how people understand language about unimanual actions (Willems et al., 2011; Gijssels, Ivry, & Casasanto, 2018), and that linguistic context can shape the manner and extent to which people rely on the motor system for processing action language (Tomasino, Weiss, & Fink, 2010; Gijssels, Zhang, Lucero, Marc, & Casasanto, in preparation; see Aravena et al., 2012, 2014 for related behavioral results).

An informal survey of the literature on action language understanding demonstrates the extent to which this research relies on manual action verbs: Most action language studies explicitly include manual action verbs in their stimulus sets, with many neuro-imaging and neuro-stimulation studies rely almost exclusively on these verbs for their conditions of interest (e.g. fMRI: Tomasino et al., 2007, 2010; Willems, Toni, et al., 2010; Willems, Hagoort, & Casasanto, 2010; Hauk & Pulvermuller, 2011; Yang, Shu, Bi, Liu, & Wang, 2011; Yang & Shu, 2014; Gijssels et al., in preparation; EEG: Boulenger, Silber, et al., 2008; Moreno, De Vega, & León, 2013; Moreno et al., 2015; Vanhoutte et al., 2015; (r)TMS: Tomasino et al., 2008; Willems et al., 2011; Tremblay, Sato, & Small, 2012; Repetto, Colombo, Cipresso, & Riva, 2013; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017).

Across these studies, researchers typically identify different types of manual action verbs by relying on participants' judgments of how they use their hands to perform the actions described by the verbs. So far, most studies have done so by having participants explicitly rate the extent to which they associate these verbs with manual actions (e.g. Hauk et al., 2004), whereas only a few studies asked participants to rate how much they rely on each hand to perform these actions (Willems, Toni, et al., 2010; Willems, Hagoort, & Casasanto, 2010; Hauk & Pulvermuller, 2011; Gijssels et al., 2018). Moreover, even when studies collected continuous ratings of the relative contributions of the left and right hand, they typically used these ratings to classify manual verbs into discrete categories (e.g. unimanual vs. bimanual vs. nonmanual), for the purpose of treating the stimuli within each category as members of an equivalence class.

Yet, with some exceptions, the assumption that all unimanual or bimanual verbs are created alike is unlikely to hold. Instead, the degree to which people rely on one vs. two hands for performing manual actions is likely to vary continuously, rather than categorically. For instance, some verbs that are categorized as unimanual may describe actions that rely exclusively on the dominant hand (e.g. ”to wave”), whereas others may describe actions that also rely on the non dominant hand (e.g.”to cut”, where the dominant hand does most of the work, but the non dominant hand plays an essential role in stabilizing the object being cut).

If some unimanual verbs describe actions that partly rely on the non dominant hand as well, then this category-internal variation could form a significant source of Type II error for studies like those cited above. For instance, whereas right-handers may show strongly left-lateralized premotor cortex activity when reading a fully unimanual verb like ”to wave”, they may show a relatively less lateralized pattern of premotor cortex activity when reading a verb like ”to cut”, thereby obscuring the predicted pattern of interest. One possible solution to this problem is to collect a measure that reflects the continuous variability in how people use their (non) dominant hand to perform manual actions, and to use that measure for constructing stimulus sets.

Here, we constructed one Dutch and one English corpus of verbs that describe manual actions and we provide norms of how people use their hands to perform those actions. First, we adopted the same explicit rating procedure that is commonly used in studies on action verb semantics. Participants read one verb at a time and explicitly rated the extent to which they typically use their left and right hand to perform each of the actions described. Second, because actions are natural to perform but notoriously difficult to put into words, we also collected an implicit measure of how people perform these actions. Before they performed the explicit rating task, participants pantomimed each of the actions in the stimulus set. Then, we coded the relative activity of the left and right hand separately, for each of the pantomimes. As such, these implicit measures allow us to quantify the way in which people typically perform a large set of manual actions, and also allow us to directly compare how people’s explicit actions ratings of their correspond to their implicit execution of the actions.

4.2 Methods

4.2.1 Participants

Dutch sample: 37 participants performed the Dutch norming experiment, all of whom were native Dutch speakers, as indicated by a language background questionnaire. We used the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) to establish participants' handedness. 3 participants were left-handed (M = -59.2; Range = -75 to -40), 31 participants were right-handed (M = 91; Range = 60 to 100), and 3 participants were ambidextrous (M = 19.5; Range = 0 to 38.5). Following Vrije Universiteit Brussel IRB guidelines, all participants provided informed consent and received 10€ for their participation.

English sample: 38 participants took part in the English norming experiment. We excluded the data from one participant for not following task instructions, and from a second participant for not being a native English speaker. All remaining 36 participants were native English speakers, based on their responses to a language background questionnaire. As indicated by their EHI scores, 4 participants were left-handed (M = -62.5; Range = -80 to -50), 28 participants were right-handed (M = 78.1; Range = 41 to 100), and 4 participants were ambidextrous (M = 27.5; Range = 20 to 37.5). Following University of Chicago IRB guidelines, all participants provided informed consent and received $10 for their participation.

Since we decided a priori to only collect and analyze data from right-handers (n = 31 Dutch right-handers, n = 28 English right-handers), all ambidextrous and left-handed participants were excluded from the analyses (n = 6 Dutch non-right-handers, n = 8 English non-right-handers).

4.2.2 Stimuli

We constructed two separate stimulus sets for the norming experiments, one in Dutch and one in English. Each of these sets consisted of manual action verbs: verbs that describe actions people typically perform using their hands (e.g. "to write" or "to untie"). Some of the verbs were selected from the stimuli of previous studies on action semantics (Willems, Hagoort, & Casasanto, 2010; Hauk & Pulvermuller, 2011; Akinina et al., 2015; Shao, Roelofs, & Meyer, 2014; Vinson & Vigliocco, 2008). Other verbs were novel additions, suggestions from thesauruses, or Dutch-English translation equivalents.

All manual verbs were included into our stimulus set, with the following constraints. First, we excluded verbs that could also be used to describe nonmanual actions (i.e. actions performed with effectors other than the hands, e.g. "to roll"). Second, since Dutch infinitives often share their word form with semantically related plural nouns, we only included those word forms that are used more frequently as verbs than as nouns (based on INL frequency from CELEX; Baayen et al., 1995). For instance, the word form "graven" is used more often as a plural noun (English: "graves") than as a verb (English: "to dig"), and was excluded from our list. After applying these constraints, each of the final stimulus sets consisted of 268 unique manual action verbs (Dutch word length: $M = 8.2$ characters; Range = 5 to 13 characters; English word length: $M = 5.12$ characters; Range = 3 to 10 characters).

Finally, for each language we also selected 32 nonmanual action verbs which served as stimuli for the catch trials in the explicit rating task (see below). Half of these stimuli described actions that are typically performed using the mouth (e.g. "bijten", "to bite"), whereas the other half described actions typically performed using the legs (e.g. "wandelen", "to walk").

4.2.3 Procedure

The norming experiments were identical for both languages, and consisted of two separate tasks: a pantomime task followed by an explicit rating task performed on the same verbs.

Pantomime task.

In the pantomime task, participants read one verb at a time and pantomimed the action described by each verb. Participants were seated on a chair without armrests in front of a computer screen. At the start of each trial, participants placed their hands in the designated resting position on their legs. Then, the experimenter pressed a button, causing the trial to start. Each trial started with a fixation cross (1s), which was then replaced by a single verb presented in its infinitive form (e.g. "schrijven" in Dutch; "to write" in English). Participants read the verb, acted out the action it described, and then returned their hands to the resting position, at which point the experimenter pressed a button causing the verb to disappear, and the next trial to start. If participants did not know the meaning of a verb, they verbally responded "pass", causing the experimenter to press a button that ended the current trial and started the next. Throughout the entire task, we videotaped all of the participants' responses. Participants received a few practice trials at the start of the implicit rating task, and received a short break halfway through the experiment. The entire stimulus set was divided into two subsets (one presented before the break and one presented after; order counterbalanced across participants). The order of the stimuli within each subset was fully randomized.

Explicit rating task.

After participants completed the pantomime task, they performed an explicit rating task on the same verbs. On each trial, participants saw a single verb on the computer screen and then answered the following sequence of questions. The first question asked: "Which body part do you usually use to perform this action?" Participants answered by pressing a button that corresponded to "hands", "mouth", or "feet" (or pressed the space bar to pass). If participants answered "mouth" or "feet", the trial ended and the next one started.

If participants answered "hands", the second question appeared which asked "Do you usually perform this action with one hand or with two hands?" Here, participants answered by pressing one of two buttons, corresponding to “one hand” or “two hands”. For the third and final question, participants provided a continuous rating indicating the relative left- to right-handedness of an action. If participants responded “one hand” on the second question, then the continuous rating prompt asked “If you use one hand, which hand do you use to perform this action?” Participants responded by selecting a value on a Likert scale ranging from 1 (“Always left hand”) to 7 (“Always right hand”), with the midpoint 4 being labeled as “No preference”. If participants responded “two hands” on the second question, then the continuous rating prompt asked “If you use two hands, which hand does most of the work to perform this action?” Participants responded by selecting a value on a Likert scale ranging from 1 (“Mainly left hand”) to 7 (“Mainly right hand”), with the midpoint 4 being labeled as “Both hands equally”. For the first and second categorical questions, the response mappings were fully counterbalanced across participants. The order of stimuli was fully randomized across participants. At the start of the task, participants received three practice trials and they received three short breaks throughout the task.

4.2.4 Data coding

To quantify the extent to which participants used each of their hands to pantomime the described actions, we trained two pairs of coders to analyze the video data from the Dutch and English experiments (one pair of coders assigned to each language). For each trial, the coders watched the video recording and then provided three separate scores indicating the relative activity of the left hand, of the right hand, and of any nonmanual effectors (e.g. the face or legs). The score for each effector could range from 0 (“No voluntary movement”) to 5 (“Voluntary, ostensive movement”), and was based on the coder’s subjective impression of each effector’s force, amount of movement, and duration of use. For instance, if a participant pantomimed “to punch” by repeatedly punching forcefully with the right hand, without moving their left hand or the rest of their body, the respective scores would be: Left Hand = 0; Right Hand = 5; Nonmanual = 0. Yet, if a participant pantomimed “to unscrew” by holding a jar in the left hand, while unscrewing the lid using the right hand, the relative scores may be: Left Hand = 3; Right Hand = 5; Nonmanual = 0. Finally, coders scored the activity levels of each effector relative to the overall activity level of all effectors combined, for a given trial. For instance, if a participant pantomimed "to pinch" by using their right hand to make a single, small pinching movement, they would receive a similar score as in the "to punch" example above (i.e. Left Hand = 0; Right Hand = 5; Nonmanual = 0), since for this trial, the right hand was the sole effector used for the entire action. In addition to the relative activity scores, coders also marked actions that were not correctly performed ("error" or "pass") or for which the participants moved their hands outside of the camera's view ("uncodeable").

Before coding the full data set, each pair of coders calibrated their coding system by coding a few participants, comparing those scores, and then agreeing on a coding approach for trials with divergent scores. After this calibration phase, each coder independently coded the rest of the data set. Based on the final set of ratings, our coders showed high levels of agreement between their ratings, both for the Dutch data set (inter-coder correlation for Left Hand Score: β= .93, R^2 = .91, $\chi^2(1) = 233.11$, $p < .0001$; Right Hand Score: β= .92, R^2 = .84, $\chi^2(1) = 358.9$, $p < .0001$; and Nonmanual Score: β= .71, R^2 = .73, $\chi^2(1) = 160.12$, $p < .0001$) and the English data set (inter-coder correlation for Left Hand Score: β= .94, R^2 = .93, $\chi^2(1) = 240.38$, $p < .0001$; Right Hand Score: β= .95 , R^2 = .90, $\chi^2(1) = 90.947$, $p < .0001$; and Nonmanual Score: β= .50, R^2 = .31, $\chi^2(1) = 66.329$, $p < .0001$).

Finally, for the explicit rating task, we coded trials as incorrect when participants gave a "pass" response or when they chose an incorrect or atypical body part for the action (e.g. a "feet" response for the verb "to chew").

4.2.5 Analyses

To be able to directly compare the explicit and implicit continuous ratings, we transformed the explicit scale so that it covered the same -5 to +5 range of the implicit scale. We converted the original 1 to 7 scale into a -5 ("Left Hand dominant") to +5 ("Right hand dominant") scale by applying the following transformation: Transformed Value = (Original Value - 4) x 5/3.

Analogously, for the implicit continuous ratings, we converted the separate hand activity scores for all of the pantomime data into a single measure that reflects the relative extent to which participants rely on the right vs. the left hand: Right Hand Dominance. For each trial, we first calculated the Right Hand Dominance for each of the two coders separately (Right Hand Score - Left Hand Score), and then averaged these two scores, arriving at a single Right Hand Dominance (RHD) value for each trial. This RHD reflects the relative activity of each of the hands for a given pantomime, and ranges from -5 ("Left Hand Only") to +5 ("Right hand Only"). Additionally, by taking the absolute value of this RHD, we also constructed a continuous measure of unimanuality, which reflects the extent to which participants rely on one vs. two hands to perform a specific action (labeled as Implicit Unimanuality in our reports).

Finally, we performed all statistical analyses using R (v. 3.5.3). For the subject-wise analyses comparing participants' implicit behavior to their explicit ratings, we used the 'lme4' package for mixed-effect analyses with maximal slopes structures (Barr et al., 2013).

4.3 Results

4.3.1 Accuracy

To identify items whose meanings were ambiguous or hard to interpret, we analyzed the overall by-item accuracy separately for each task and language. Most items were classified with high accuracy, in both the explicit tasks (Dutch: *M* = 93.25%, *SD* = 14%; English: *M* = 97.7%, *SD* = 4.77) and the implicit tasks (Dutch: *M* = 91.33%, *SD* = 15.44; English: *M* = 94.34%, *SD* = 11.3). To identify items with markedly low accuracy, we performed an outlier exclusion by removing any items with a mean accuracy 2.5 SDs below the task mean (Dutch verbs: 17 manual and 1 nonmanual excluded; English verbs: 18 manual and 1 nonmanual excluded). The final set of items used for the analyses consisted of 251 Dutch manual stimuli, 250 English manual stimuli.

Then, we analyzed the by-participant accuracy to ensure all participants performed the task correctly. Most participants had high accuracy in the explicit tasks (Dutch: $M = 95.77\%$, SD=3.88; English: $M = 98.4\%$, $SD = 1.32$) as well as in the implicit tasks (Dutch: $M = 93.93\%$, $SD = 6.32$; English: $M = 95.95\%$, $SD = 4.26$). Two participants in the Dutch experiment and two participants in the English experiment had accuracy scores 2.5SDs below the group mean in one or both tasks, and were excluded from further analyses.

4.3.2 Variability in hand use across and within items

Across all types of ratings, manual actions in both languages showed wide variability in the extent to which they relied on the left and right hand. First, verbs differed in how consistently they were categorized as being unimanual or bimanual. Whereas some verbs were never classified as being unimanual (e.g. "to type": $M = 0\%$ unimanual) and others were always classified as unimanual (e.g. "to point": $M = 100\%$ unimanual), the average categorization of most items was somewhere in between: The average proportions of unimanual categorizations

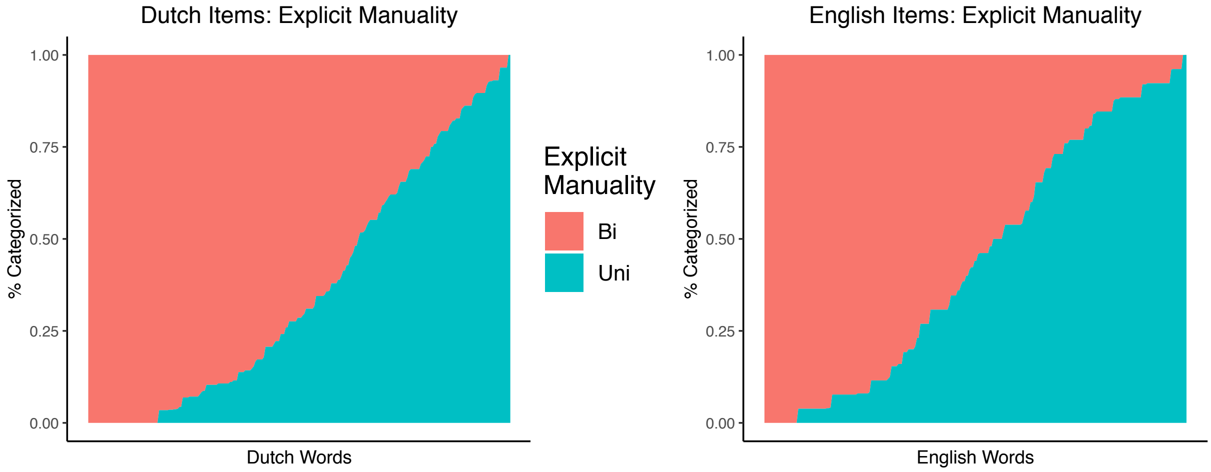

Figure 4.1: Item-wise averages of explicit manuality categorizations. Left: Dutch verbs; Right: English verbs.

for all items show a continuous distribution from 0 to 100% (Dutch: $M = 36.75\%$; English: $M = 44.81\%$; see Figure 4.1).

Second, the items also differed in the extent to which participants pantomimed them using the right hand exclusively. The mean Right Hand Dominance (RHD) scores for each of the verbs covered a wide range, not only for verbs that were explicitly categorized as being bimanual (Dutch: $M = 1.28$; Range = -.03 to 4; English: $M = 1.03$; Range = -.15 to 4.1) but also for verbs that were categorized as unimanual (Dutch: $M = 3.69$; Range = 1.23 to 4.96; English: $M = 3.5$; Range = -.08 to 5; see Figure 4.2 and 4.3).

Finally, manual actions varied in how consistently participants pantomimed the same action in the same way. One source of inconsistency stems from different participants varying in how much they used their left hand to pantomime the same action, as reflected in the variation in SEMs of the item-wise RHD scores (Dutch SEM range: .06 to .66; English SEM range: .06 to 1.03; see Figures 4.2 and 4.3; Tables 6.1 and 6.1). A second source of inconsistency is that for some items, participants used only one hand to pantomime the action, yet were equally likely to use their left or right hand to do so, as indicated by an item's low average RHD and high Implicit Unimanuality score (e.g. "to nudge"; see Tables 6.1 and 6.1).

4.3.3 Correspondence between implicit and explicit ratings

The average explicit ratings for the manual items were significantly correlated with their average implicit ratings. The proportion of unimanual categorizations for an item predicted that item's average Implicit Unimanuality score ($\beta= 4.24$; $t(499) = 50.06$; $p < .0001$; $R^2 = .83$). Moreover, an item's average explicit continuous rating predicted its average RHD, both for bimanual verbs ($\beta= .81$; $t(300) = 22.71$; $p < .0001$, $R^2 = .64$) and unimanual verbs ($\beta=.63$; $t(197) = 9.61$; $p < .0001$; $R^2=.32$).

Similarly participants' explicit ratings for individual items also significantly predicted their corresponding implicit ratings, even though these ratings explained substantially less variance in the data. The way in which a participant explicitly categorized an action predicted their Implicit Unimanuality score for that action (β= 1.08, $t(114) = 15.76$, $p < .0001$; $R^2 = .08$), and their explicit continuous ratings predicted the RHD score of their pantomimes, both for verbs they categorized as bimanual verbs (β= .19, $t(72) = 9.79$, $p < .0001$; $R^2 =$ .03), and as unimanual (β= .17, $t(64.31)$ =4.5, $p < .0001$, $R^2 = .01$).

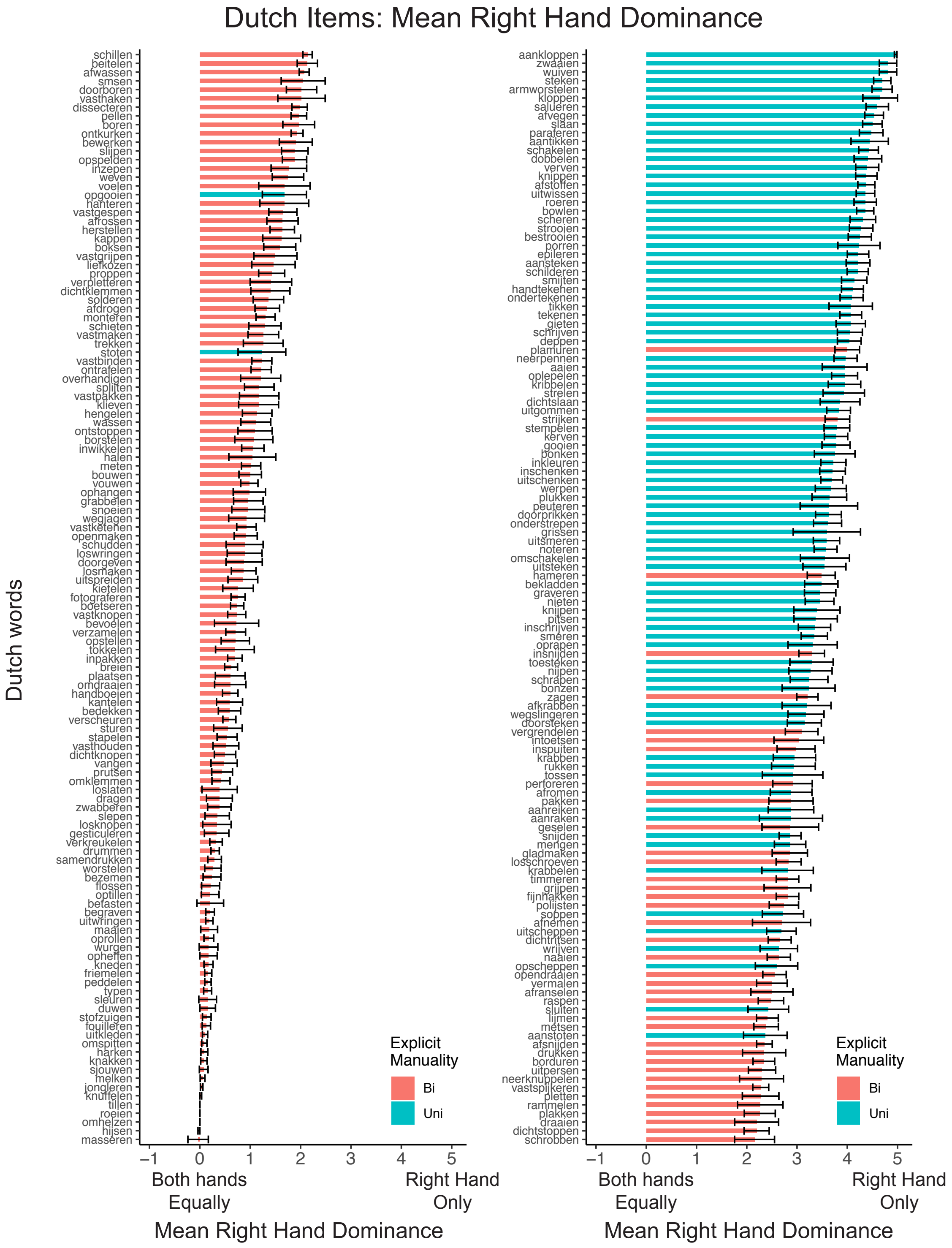

Figure 4.2: Item-wise RHD scores for Dutch verbs, averaged across participants. Each verb's explicit categorization (Bimanual vs. Unimanual) was assigned based on the option chosen by most participants. Error-bars reflect SEM. Note: Plot separated into two for legibility.

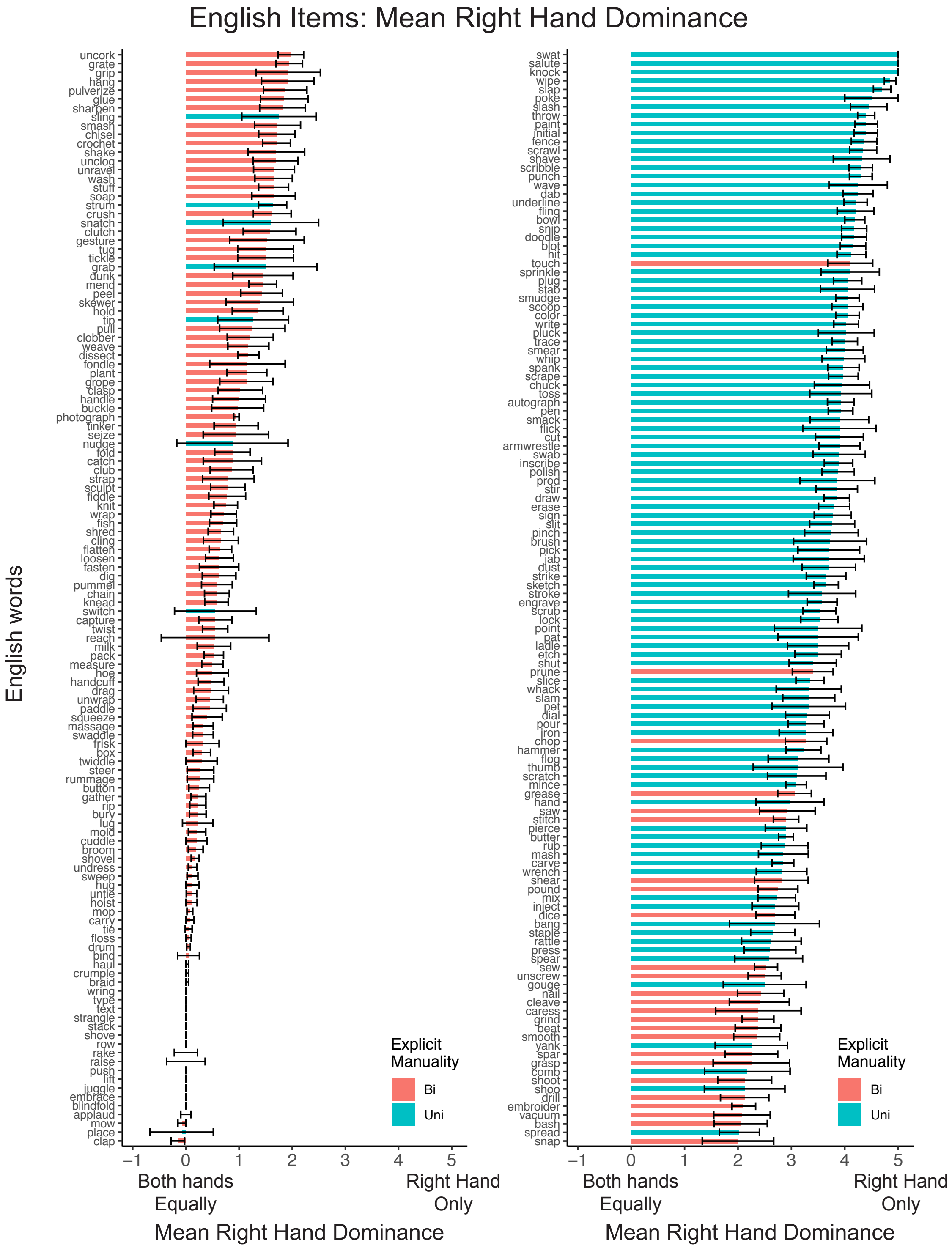

Figure 4.3: Item-wise RHD scores for English verbs, averaged across participants. Each verb's explicit categorization (Bimanual vs. Unimanual) was assigned based on the option chosen by most participants. Error-bars reflect SEM. Note: Plot separated into two for legibility.

4.4 Discussion

Here, we constructed corpora of Dutch and English manual action verbs and provided continuous measures of how people use their left and right hands to perform the actions described by these verbs. We collected implicit measures of hand use by having right-handed participants pantomime the manual actions described by each of the verbs. In addition, participants explicitly rated how each of their hands contributes to performing these actions. Our results demonstrate that unimanuality (i.e. whether an action is performed with only one hand or both hands) varies continuously, rather than categorically: Participants pantomimed most actions using both their right and left hand, for so-called "unimanual" and "bimanual" actions alike, with the relative contribution of their left hand varying continuously across the different stimuli. Additionally, by comparing participants' explicit and implicit ratings, we found only limited support for the assumption that people can explicitly report on their procedural knowledge of actions. accurately. When averaging across items, the explicit ratings showed a moderate correlation with participants' implicit behavior, yet within an individual participant, explicit reports only explained a small fraction of the variance in how people performed actions (between 1 and 3 percent). Together, these data show that not all unimanual and bimanual action verbs are created alike, and underscore the importance of using implicitly measured continuous norms for studying the representation of manual action verbs.

4.4.1 Using manuality norms to test Embodied Cognition

Many studies have used manual action verbs to test theories of embodied cognition, and several have done so by leveraging the hemispheric lateralization of systems for manual action. Yet, most of these studies either do not empirically establish the manuality of their stimuli (e.g. Repetto et al., 2013), or treat manuality in a categorical way by classifying their stimuli as being either unimanual or bimanual (e.g. Willems, Hagoort, & Casasanto, 2010; Niccolai et al., 2014; Vukovic et al., 2017).

The current results show that few actions are either exclusively unimanual or symmetrically bimanual: People pantomimed most actions by using both hands, although the contribution of the left hand varied continuously across items. This pattern suggests that treating manuality as a categorical distinction obscures the continuous variation in how people perform manual actions, and may be a significant source of Type II error in experiments that posit hemispheric specialization for unimanual actions, or a right- vs. left-hand advantage in behavioral responses. That is, if actions that are assumed to be performed unimanually with the dominant hand also rely on the non dominant hand, then the neural and behavioral responses to verbs describing these actions may show less specificity than expected, thereby decreasing a study's power to detect the predicted results.

By providing a set of measures that quantify the variation in how people perform manual actions, these corpora offer researchers increased control over their stimulus selection, which in turn should allow them to minimize this form of Type II error. For instance, by selecting items with high mean RHD and high Implicit Unimanuality scores, researchers can construct a set of verbs describing actions that mostly rely on the right hand. Whereas we provide the item-wise averages for the the relevant measures in Tables 6.1 and 6.1, we will also provide full access to the raw data and R code through OSF, allowing researchers to construct their own measures.

4.4.2 Do explicit ratings reflect implicit behavior?

To select stimuli for experiments on embodied cognition, researchers typically use norms of the extent to which different words elicit specific perceptuo-motor experiences (e.g. Lynott & Connell, 2009). Often, these norms are constructed by having participants explicitly rate words on a set of theoretically relevant dimensions, based on the assumption that participants' explicit ratings will accurately reflect their implicit knowledge. Yet, whether this assumption is valid remains unclear, especially when considering explicit ratings of procedural domains (e.g. action), which are notoriously hard to access declaratively.

Here, we show that people's explicit ratings of hand use significantly predict some of the variance in how they actually enact those actions through pantomime, yet the explicit ratings also leave large amounts of the variance unexplained. At the group-level, participants' judgments reliably reflected whether an action is performed with one or two hands, yet judgments were markedly less reliable in reflecting the continuous variation in each hand's relative contribution to a given action. However, an individual participant's explicit ratings captured very little of the variance in their overt behavior, suggesting that people are not able to reliably report on their own actions. Therefore, even though explicit norms may be easier to collect and may provide a moderately reliable approximation of categorical distinctions when ratings are averaged across items, our results suggest that implicit measures provide a more reliable index of continuous distinctions, especially at the level of the individual item, and the individual person.

4.4.3 Do manual pantomimes accurately reflect how people perform manual actions?

Although pantomimes share many behavioral and neural similarities with the actions they depict (see e.g. Weiss, Jeannerod, Paulignan, & Freund, 2000 and Grèzes, Armony, Rowe, & Passingham, 2003), they also diverge in several ways: Pantomimes and real manual actions differ in some of their kinematic properties (e.g. grip aperture or velocity; Senkfor, 2008; Goodale, Jakobson, & Keillor, 1994; Laimgruber, Goldenberg, & Hermsdörfer, 2005), as well as in the cognitive processes they rely on (Frey, 2008). That is, whereas manual actions are typically highly detailed and non-communicative, pantomimes are often schematic and used for communicative purposes (Senkfor, 2008; Cartmill, Beilock, & Goldin-Meadow, 2012).

Do these differences between how people pantomime and perform manual actions pose a problem for using the current corpora? Not necessarily. Our main goal was to provide a measure that allows researchers to predict the extent to which people show lateralized motor system activity when processing language about manual actions, and these pantomime ratings provide a reliable way of doing so, for several reasons. First, whereas explicit ratings of manual actions provide a declarative measure of procedural action knowledge, our pantomime ratings likely offer a better approximation of manual action performance because pantomimes also rely on procedural representations. Second, even though the schematic nature of pantomimes may make them less similar to the manual actions they depict, this schematicity may make them more similar to language-induced motor simulations. Just as people's pantomimes reflect manual actions in an impoverished setting (i.e. a setting that does not specify the relevant objects, tools, or other contextual constraints), so too do the linguistic stimuli that are typically used in studies of action language processing. For instance, in these studies, action verbs are typically presented in their infinitive forms (e.g. "to grab"), leaving many contextual aspects of the action unspecified, which may lead participants to simulate these actions in ways that are more sparse and schematic than when they would actually perform these actions (see Willems, Toni, et al., 2010 for discussion).

Together, the procedural and schematic nature of pantomimes turn them into reasonable approximations of the way in which people simulate actions during language understanding. Nonetheless, whereas these pantomime norms may be appropriate for constructing stimuli to test action language understanding, they should be used with caution in studies that want to construct stimuli for testing overt execution of manual actions, in which case they may need additional verification.

4.4.4 Dominant hand bias for manual actions

In this study, people used both hands to perform most manual actions, including those actions they explicitly classified as being unimanual. Yet, our data also show that for the majority of these actions people relied more on their dominant hand than on their non dominant hand. This dominant hand bias was not restricted to verbs classified as being unimanual, but extended to the ones categorized as being bimanual as well (mean RHD of bimanual verbs > 0: Dutch: $t(160) = 15.56$; $p < .0001$; English: $t(136) = 13.23$; $p < .0001$). This finding confirms previous suggestions that when people perform bimanual actions, they rarely use both hands to an equal extent, but instead divide the workload asymmetrically across both hands. For instance, when hammering a nail into a wall, right-handers typically use their left hand to stabilize the nail whereas their right hand does the more effortful job of hammering it (see Guiard & Ferrand, 1996; Guiard, 1987).

This dominant hand bias may also explain why several neuro-imaging studies found left-lateralized patterns of motor system activity when participants processed manual action verbs, even though these verbs were not explicitly selected to be unimanual (e.g. Hauk et al., 2004; Aziz-Zadeh et al., 2006; Tettamanti et al., 2005). Since most of these previous studies exclusively tested right-handers, and since our data show that, on average, manual action verbs have a dominant hand bias, participants in these studies likely processed these verbs as describing actions that rely more strongly on the right than on the left hand. As a result, these participants were likely to show stronger activity in left hemisphere motor areas that control the right hand compared to right hemisphere motor systems that control the left hand, even for "bimanual" actions, thereby offering a possible explanation of the left-lateralized patterns of motor activation in these studies.

4.4.5 Do left-handers' manual actions mirror right-handers' actions?

Although we intended to collect data from right-handers alone, a few left-handers incidentally participated in our experiments. Given the small number of left-handed participants (Dutch: $n = 3$; English: $n = 4$), we did not have sufficient power to include them in our statistical analyses. Nonetheless, we performed an exploratory analysis that asked whether the distribution of left-handers' pantomimes provided a mirror image of the distribution of the right-handers' pantomimes (see supplementary Figure 6.1). This analysis suggests that, compared to right-handers, the left-handers relied less on their dominant (i.e. left) hand and more on their non-dominant (i.e. right) hand when pantomiming manual actions, as indicated by the rightward shift in the peaks for both the unimanual and bimanual actions and by the long rightwards tails of the left-hander distributions.

This reduced dominant hand bias in left-handers matches the observations of previous studies (Willems et al., 2009) and may offer a possible explanation for why left-handers show weaker patterns of lateralized neural activity when processing language describing unimanual actions than right-handers. If, compared to right-handers, left-handers rely more on their non dominant hand for performing unimanual actions, then they should also show stronger activity in motor circuits controlling the non dominant hand when processing language about those actions (see Willems et al., 2009; Willems, Hagoort, & Casasanto, 2010 for a reduced neural asymmetry in left-handers; for similar findings in behavioral tasks, see: De Nooijer, Van Gog, Paas, & Zwaan, 2013; Chrysikou, Casasanto, & Thompson-Schill, 2017; Apel, Cangelosi, Ellis, Goslin, & Fischer, 2012.

Why would left-handers show a weaker dominant hand bias for manual actions? On one possibility, left-handers may simply have a weaker hand preference than right-handers, overall: In several large-sample studies, strong left-handers are proportionally underrepresented compared to strong right-handers (Annett, 2004; Andersen & Siebner, 2018). On a second, non mutually-exclusive explanation, left-handers may have to use their non-dominant hand more often because they live in a right-handed world and therefore frequently have to interact with objects designed for right-handers (Chrysikou et al., 2017).

Regardless of why left-handers show a reduced dominant hand bias, these preliminary data suggest that this bias exists across a range of manual actions, and that separate implicit norms of hand use may be needed for testing this population.

CHAPTER 5

CONCLUSION

Across three experiments, I tested how people construct the meaning of action language. Our fMRI data show that people understand the same action words in different ways, depending on the specifics of their own bodies, and on whose actions are being described. When performing language-induced imagery of our own actions, premotor cortex activity reflects how we use our own bodies. Yet, when performing imagery of others' actions, premotor activity also reflects how others use their bodies. In the second experiment, by experimentally manipulating neural activity in premotor cortex, I show that premotor cortex activity not only correlates with, but also causally contributes to how well people process the meaning of action language. In the final experiment, I provide two corpora of continuous measures of how people use their hands to perform a large collection of manual actions. These corpora provide a precision-tool for testing whether the way in which people simulate a given action verb reflects how they typically use their body to perform that action.

On most standard views of language processing, the format of people's semantic representations can be studied independently of the brain systems that implement them. By contrast, embodied accounts propose that the way in which people represent the meaning of words depends on which neural systems they use to experience their referents. The format of semantic representations differs in a modality-specific way, depending on the perceptuo-motor systems that implement them. As a result, the only way to test embodied theories is to simultaneously probe the behavioral and neural processes that underlie people's language understanding (see Casasanto & Gijssels, 2015, for discussion). Here, we use this approach to show not only *that* perceptuo-motor systems contribute to language understanding, but also to elucidate *what kinds of knowledge* these neural systems contribute to how people understand the meanings of words. Just as people's perceptuo-motor systems reflect their experience of perceiving and acting on the world, so do the linguistic processes that rely on these systems: People construct the meanings of words by drawing on the relevant aspects of their bodily and social experience.

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CHAPTER 6

APPENDIX

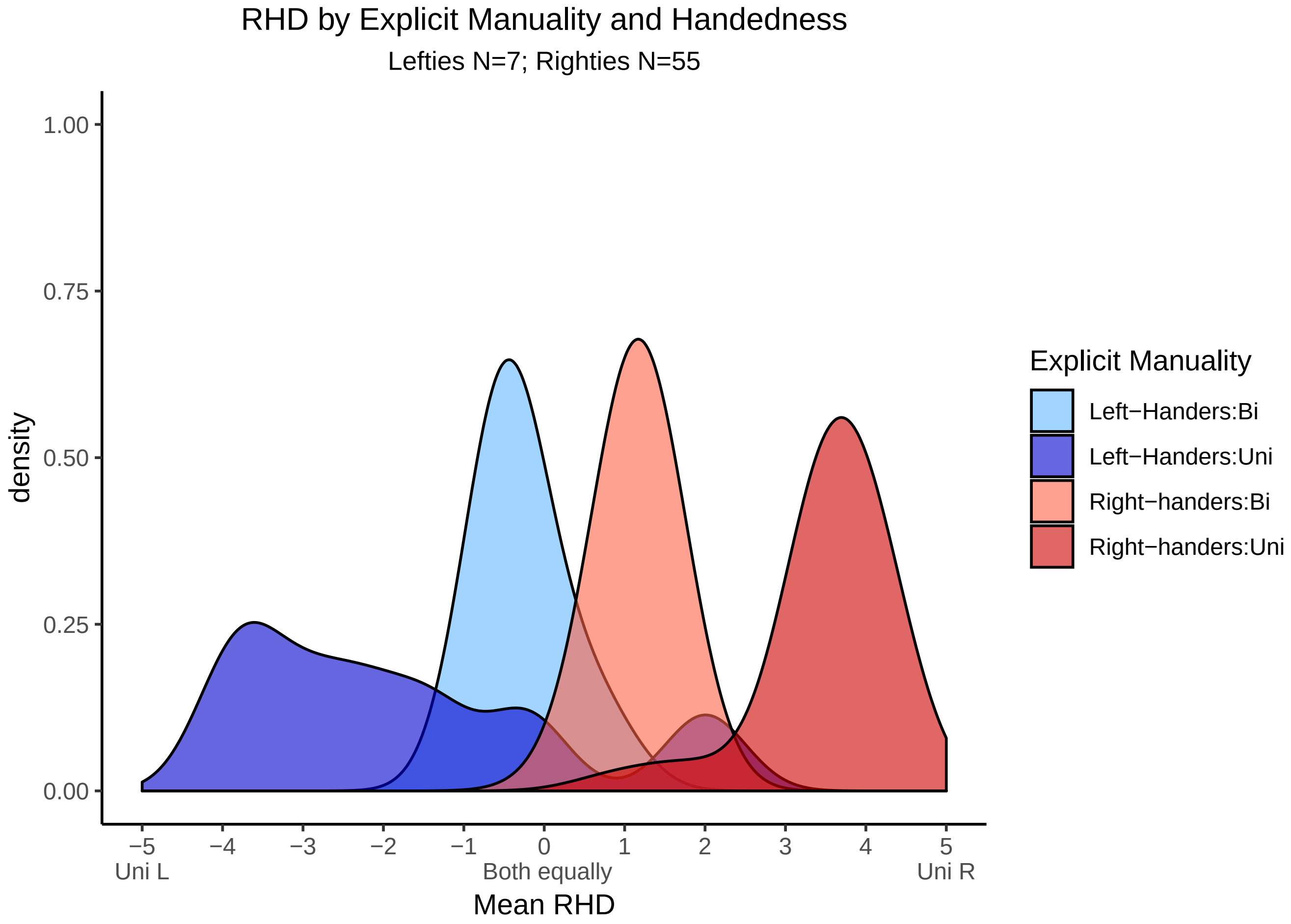

Figure 6.1: Density plot of subject-wise average RHD, collapsed across languages. Blue = Left-handers; Red = Right-handers. Dark = Unimanual; Light = Bimanual.

Table 6.1: Dutch Item-wise statistics. % Accuracy based on pantomime data. Max.Cat.: Category label maximally assigned. Impl. Uni.: Average Implicit Unimanuality. Expl.Cont: Explicit Continuous Rating transformed. See Analysis section for information on how these variables were calculated.

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
aaien	1.00	Uni	0.14	0.86	3.95	0.45	4.50	3.28
aankloppen	0.97	Uni	0.00	1.00	4.96	0.03	4.96	4.20
aanraken	1.00	Uni	0.34	0.66	2.88	0.63	4.12	2.41
aanreiken	1.00	Uni	0.38	0.62	2.88	0.45	2.95	1.95
aansteken	0.97	Uni	0.25	0.75	4.21	0.24	4.21	3.87
aanstoten	0.81	Uni	0.41	0.59	2.37	0.43	2.54	2.12
aantikken	0.97	Uni	0.07	0.93	4.45	0.37	4.80	3.56
afdrogen	0.97	Bi	1.00	0.00	1.34	0.24	1.38	1.78
afkrabben	1.00	Uni	0.38	0.62	3.19	0.49	3.78	3.22
afnemen	0.90	Bi	0.57	0.43	2.69	0.58	3.38	2.26
afranselen	0.87	Bi	0.89	0.11	2.50	0.42	2.50	1.90
afromen	0.55	Uni	0.48	0.52	2.88	0.41	2.88	3.41
afrossen	0.84	Bi	0.88	0.12	1.64	0.31	1.68	1.67
afsnijden	0.97	Bi	0.69	0.31	2.35	0.16	2.35	3.79
afstoffen	1.00	Uni	0.17	0.83	4.38	0.17	4.38	4.14
afvegen	1.00	Uni	0.15	0.85	4.53	0.19	4.53	3.95
afwassen	0.97	Bi	1.00	0.00	2.07	0.10	2.07	2.07
armworstelen	0.90	Uni	0.14	0.86	4.69	0.20	4.69	4.20
bedekken	0.97	Bi	1.00	0.00	0.59	0.22	0.62	1.09
begraven	0.94	Bi	1.00	0.00	0.20	0.09	0.20	1.25
beitelen	0.94	Bi	0.90	0.10	2.13	0.20	2.25	3.28
bekladden	0.97	Uni	0.43	0.57	3.48	0.33	3.48	3.27

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
bestrooien	0.97	Uni	0.17	0.83	4.25	0.23	4.25	3.91
betasten	1.00	Bi	0.90	0.10	0.21	0.26	0.69	1.15
bevoelen	0.81	Bi	0.89	0.11	0.73	0.44	1.15	0.93
bewerken	0.71	Bi	0.88	0.12	1.90	0.33	1.90	2.18
bezemen	0.97	Bi	1.00	0.00	0.24	0.18	0.28	1.95
boetseren	0.94	Bi	1.00	0.00	0.74	0.13	0.74	1.26
boksen	1.00	Bi	1.00	0.00	1.59	0.32	1.72	2.07
bonken	0.94	Uni	0.38	0.62	3.75	0.40	3.75	3.08
bonzen	0.90	Uni	0.38	0.62	3.23	0.53	3.62	2.99
borduren	0.87	Bi	0.78	0.22	2.34	0.22	2.34	3.15
boren	1.00	Bi	0.90	0.10	1.96	0.32	1.96	2.82
borstelen	1.00	Bi	0.76	0.24	1.07	0.38	1.14	2.41
bouwen	0.97	Bi	1.00	0.00	1.00	0.22	1.04	1.67
bowlen	0.97	Uni	0.11	0.89	4.36	0.17	4.36	4.58
breien	1.00	Bi	1.00	0.00	0.62	0.13	0.62	1.09
deppen	0.87	Uni	0.18	0.82	4.04	0.24	4.04	3.93
dichtklemmen	0.87	Bi	0.96	0.04	1.40	0.39	1.52	1.59
dichtknopen	1.00	Bi	1.00	0.00	0.50	0.21	0.57	1.61
dichtritsen	1.00	Bi	0.79	0.21	2.66	0.23	2.76	3.39
dichtslaan	1.00	Uni	0.17	0.83	3.86	0.39	4.21	3.33
dichtstoppen	0.97	Bi	0.82	0.18	2.20	0.25	2.20	1.96
dissecteren	0.90	Bi	0.93	0.07	1.98	0.15	1.98	2.50
dobbelen	0.97	Uni	0.21	0.79	4.41	0.27	4.45	3.85
doorboren	0.97	Bi	0.72	0.28	2.02	0.30	2.02	2.93

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
doorgeven	1.00	Bi	0.64	0.36	0.88	0.36	0.98	1.61
doorprikken	0.97	Uni	0.41	0.59	3.62	0.26	3.62	3.95
doorsteken	0.84	Uni	0.22	0.78	3.15	0.34	3.15	4.07
draaien	0.97	Bi	0.71	0.29	2.20	0.44	2.30	1.83
dragen	0.97	Bi	0.89	0.11	0.39	0.26	0.39	1.01
drukken	1.00	Bi	0.54	0.46	2.34	0.43	2.34	2.02
drummen	0.97	Bi	1.00	0.00	0.30	0.08	0.30	0.52
duwen	1.00	Bi	0.93	0.07	0.16	0.16	0.16	0.54
epileren	0.97	Uni	0.36	0.64	4.21	0.21	4.21	3.93
fijnhakken	1.00	Bi	0.62	0.38	2.81	0.22	2.81	4.14
flossen	0.97	Bi	0.96	0.04	0.21	0.18	0.21	0.38
fotograferen	1.00	Bi	0.90	0.10	0.76	0.14	0.76	2.82
fouilleren	0.97	Bi	1.00	0.00	0.13	0.08	0.17	0.29
friemelen	0.94	Bi	0.93	0.07	0.17	0.07	0.20	1.01
geselen	0.55	Bi	0.57	0.43	2.87	0.56	2.93	2.62
gesticuleren	0.71	Bi	1.00	0.00	0.33	0.24	0.38	0.63
gieten	1.00	Uni	0.24	0.76	4.07	0.29	4.07	3.97
gladmaken	0.97	Bi	0.69	0.31	2.86	0.35	2.86	2.24
gooien	1.00	Uni	0.10	0.90	3.78	0.28	3.78	3.91
grabbelen	0.94	Bi	0.69	0.31	0.96	0.29	0.96	1.90
graveren	0.87	Uni	0.48	0.52	3.46	0.31	3.46	3.91
grijpen	1.00	Bi	0.66	0.34	2.81	0.47	2.95	2.47
grissen	0.55	Uni	0.32	0.68	3.59	0.67	4.16	3.33
halen	0.84	Bi	0.60	0.40	1.04	0.47	1.46	1.92

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
hameren	0.97	Bi	0.50	0.50	3.48	0.28	3.48	3.99
handboeien	1.00	Bi	0.86	0.14	0.60	0.15	0.60	1.31
handtekenen	1.00	Uni	0.07	0.93	4.10	0.22	4.10	4.83
hanteren	0.55	Bi	0.55	0.45	1.68	0.48	1.68	1.82
harken	0.97	Bi	0.97	0.03	0.09	0.07	0.16	1.90
hengelen	1.00	Bi	0.86	0.14	1.14	0.29	1.14	1.95
herstellen	0.74	Bi	0.97	0.03	1.64	0.24	1.64	1.90
hijsen	0.94	Bi	0.93	0.07	-0.02	0.02	0.02	0.48
inkleuren	1.00	Uni	0.14	0.86	3.72	0.25	3.72	4.71
inpakken	0.97	Bi	1.00	0.00	0.70	0.14	0.73	1.49
inschenken	1.00	Uni	0.31	0.69	3.71	0.25	3.71	3.85
inschrijven	0.81	Uni	0.12	0.88	3.35	0.32	3.35	4.36
insnijden	0.84	Bi	0.52	0.48	3.29	0.26	3.29	3.95
inspuiten	0.97	Bi	0.55	0.45	2.98	0.38	3.38	4.08
intoetsen	0.97	Bi	0.69	0.31	3.04	0.50	3.39	2.13
inwikkelen	1.00	Bi	1.00	0.00	1.05	0.22	1.19	1.09
inzepen	0.97	Bi	0.66	0.34	1.77	0.35	1.80	2.24
jongleren	0.97	Bi	1.00	0.00	0.04	0.02	0.04	0.17
kantelen	0.97	Bi	0.92	0.08	0.59	0.26	0.66	1.15
kappen	0.97	Bi	0.72	0.28	1.62	0.38	1.62	2.41
kerven	1.00	Uni	0.31	0.69	3.78	0.23	3.78	3.68
kietelen	1.00	Bi	0.93	0.07	0.76	0.30	0.79	0.98
klieven	0.68	Bi	0.91	0.09	1.17	0.40	1.17	1.74
kloppen	1.00	Uni	0.03	0.97	4.66	0.34	5.00	3.91

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
knakken	0.84	Bi	1.00	0.00	0.08	0.06	0.08	0.45
kneden	1.00	Bi	1.00	0.00	0.17	0.09	0.17	0.69
knijpen	1.00	Uni	0.28	0.72	3.40	0.46	3.74	2.99
knippen	1.00	Uni	0.31	0.69	4.38	0.21	4.38	4.43
knuffelen	0.97	Bi	1.00	0.00	0.02	0.02	0.02	0.18
krabbelen	0.81	Uni	0.33	0.67	2.81	0.51	3.23	3.40
krabben	1.00	Uni	0.21	0.79	2.95	0.42	3.22	2.87
kribbelen	0.90	Uni	0.19	0.81	3.94	0.32	3.94	4.29
liefkozen	0.87	Bi	0.83	0.17	1.46	0.43	1.62	1.02
lijmen	0.97	Bi	0.59	0.41	2.41	0.22	2.41	3.45
losknopen	1.00	Bi	1.00	0.00	0.34	0.28	0.73	1.78
loslaten	0.97	Bi	0.74	0.26	0.39	0.35	0.79	0.68
losmaken	0.90	Bi	1.00	0.00	0.87	0.24	0.91	1.49
losschroeven	0.97	Bi	0.69	0.31	2.83	0.25	2.83	3.62
loswringen	0.97	Bi	0.88	0.12	0.89	0.35	1.30	1.86
maaien	0.94	Bi	1.00	0.00	0.19	0.17	0.19	0.31
masseren	1.00	Bi	1.00	0.00	-0.03	0.20	0.31	0.42
melken	0.97	Bi	1.00	0.00	0.05	0.05	0.12	0.23
mengen	1.00	Uni	0.45	0.55	2.86	0.31	2.86	3.33
meten	0.97	Bi	0.93	0.07	1.02	0.19	1.16	1.61
metsen	0.90	Bi	0.86	0.14	2.38	0.24	2.38	2.62
monteren	0.81	Bi	0.96	0.04	1.30	0.19	1.30	2.02
naaien	1.00	Bi	0.79	0.21	2.64	0.23	2.64	3.68
neerknuppelen	1.00	Bi	0.66	0.34	2.29	0.44	2.29	2.76

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
neerpennen	1.00	Uni	0.03	0.97	3.97	0.23	3.97	4.89
nieten	1.00	Uni	0.48	0.52	3.45	0.29	3.45	3.97
nijpen	0.97	Uni	0.18	0.82	3.27	0.43	3.48	3.21
noteren	1.00	Uni	0.10	0.90	3.57	0.23	3.57	4.83
omdraaien	1.00	Bi	0.61	0.39	0.60	0.31	0.91	2.22
omhelzen	1.00	Bi	1.00	0.00	0.00	0.00	0.00	0.34
omklemmen	0.84	Bi	0.89	0.11	0.42	0.18	0.46	1.11
omschakelen	0.61	Uni	0.29	0.71	3.56	0.49	3.56	3.49
omspitten	0.97	Bi	0.96	0.04	0.09	0.05	0.09	2.04
onderstrepen	0.97	Uni	0.10	0.90	3.61	0.28	3.61	4.54
ondertekenen	1.00	Uni	0.03	0.97	4.09	0.23	4.09	4.89
ontkurken	1.00	Bi	0.97	0.03	1.93	0.12	1.93	3.16
ontrafelen	0.81	Bi	0.93	0.07	1.22	0.20	1.22	2.26
ontstoppen	0.90	Bi	0.89	0.11	1.10	0.34	1.10	2.26
opendraaien	1.00	Bi	0.83	0.17	2.55	0.23	2.66	3.05
openmaken	0.97	Bi	0.90	0.10	0.91	0.23	0.91	1.67
opgooien	0.97	Uni	0.46	0.54	1.68	0.44	1.68	2.44
ophangen	1.00	Bi	0.86	0.14	0.98	0.32	1.05	2.18
opheffen	1.00	Bi	1.00	0.00	0.17	0.17	0.17	0.46
oplepelen	0.94	Uni	0.21	0.79	3.95	0.26	3.95	4.20
oprapen	1.00	Uni	0.31	0.69	3.31	0.49	3.66	3.28
oprollen	0.97	Bi	1.00	0.00	0.18	0.10	0.25	0.75
opscheppen	0.94	Uni	0.30	0.70	2.59	0.42	2.96	4.01
opspelden	1.00	Bi	0.64	0.36	1.88	0.24	1.88	3.04

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
opstellen	0.77	Bi	0.85	0.15	0.70	0.28	0.80	1.92
optillen	1.00	Bi	1.00	0.00	0.21	0.17	0.21	0.46
overhandigen	1.00	Bi	0.72	0.28	1.21	0.40	1.21	1.32
pakken	1.00	Bi	0.62	0.38	2.88	0.44	2.88	1.90
paraferen	0.68	Uni	0.08	0.92	4.48	0.24	4.48	4.51
peddelen	0.97	Bi	0.96	0.04	0.16	0.06	0.16	0.80
pellen	1.00	Bi	0.86	0.14	1.97	0.15	1.97	3.28
perforeren	0.97	Bi	0.59	0.41	2.91	0.39	3.20	2.82
peuteren	0.90	Uni	0.19	0.81	3.63	0.57	4.40	3.52
pitsen	0.94	Uni	0.07	0.93	3.37	0.43	3.89	3.39
plaatsen	1.00	Bi	0.74	0.26	0.60	0.30	0.60	1.91
plakken	0.93	Bi	0.79	0.21	2.26	0.31	2.26	2.14
plamuren	0.90	Bi	0.52	0.48	4.00	0.24	4.00	3.70
pletten	1.00	Bi	0.64	0.36	2.28	0.36	2.31	2.47
plukken	1.00	Uni	0.34	0.66	3.64	0.34	3.64	3.68
polijsten	0.77	Bi	0.71	0.29	2.74	0.29	2.78	2.78
porren	0.97	Uni	0.07	0.93	4.23	0.42	4.59	3.62
proppen	0.94	Bi	0.86	0.14	1.43	0.26	1.43	2.14
prutsen	0.90	Bi	0.89	0.11	0.44	0.21	0.60	1.55
rammelen	0.97	Bi	0.78	0.22	2.27	0.45	2.27	1.54
raspen	0.94	Bi	0.89	0.11	2.48	0.25	2.63	3.39
roeien	0.97	Bi	1.00	0.00	0.00	0.00	0.00	0.18
roeren	0.94	Uni	0.34	0.66	4.36	0.22	4.36	3.68
rukken	0.97	Uni	0.39	0.61	2.93	0.44	2.93	2.56

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
salueren	0.90	Uni	0.00	1.00	4.60	0.22	4.60	4.38
samendrukken	1.00	Bi	0.97	0.03	0.29	0.13	0.29	1.09
schakelen	0.94	Uni	0.10	0.90	4.42	0.20	4.42	4.60
scheren	1.00	Uni	0.31	0.69	4.31	0.25	4.31	4.37
schieten	1.00	Bi	0.72	0.28	1.29	0.32	1.36	3.28
schilderen	1.00	Uni	0.14	0.86	4.21	0.21	4.21	4.20
schillen	1.00	Bi	0.93	0.07	2.14	0.09	2.14	3.10
schrapen	0.87	Uni	0.40	0.60	3.24	0.37	3.24	3.73
schrijven	1.00	Uni	0.07	0.93	4.05	0.25	4.05	4.82
schrobben	1.00	Bi	0.71	0.29	2.16	0.40	2.16	2.74
schudden	0.94	Bi	0.72	0.28	0.89	0.37	0.89	1.38
sjouwen	0.87	Bi	0.96	0.04	0.08	0.09	0.15	0.83
slaan	1.00	Uni	0.07	0.93	4.50	0.19	4.50	3.79
slepen	1.00	Bi	0.90	0.10	0.34	0.24	0.41	0.80
sleuren	1.00	Bi	0.89	0.11	0.16	0.18	0.22	0.95
slijpen	0.90	Bi	0.85	0.15	1.88	0.26	2.00	3.02
sluiten	0.97	Uni	0.43	0.57	2.43	0.40	2.43	2.86
smeren	1.00	Uni	0.38	0.62	3.34	0.26	3.34	3.51
smijten	1.00	Uni	0.14	0.86	4.14	0.25	4.14	3.68
smsen	1.00	Bi	0.66	0.34	2.05	0.44	2.05	2.41
snijden	1.00	Uni	0.45	0.55	2.86	0.22	2.86	3.97
snoeien	0.94	Bi	0.93	0.07	0.96	0.33	0.96	2.36
solderen	0.61	Bi	0.68	0.32	1.36	0.30	1.53	3.11
soppen	0.81	Uni	0.48	0.52	2.72	0.41	2.76	2.41

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
splijten	0.87	Bi	0.78	0.22	1.18	0.29	1.18	1.98
stapelen	1.00	Bi	1.00	0.00	0.54	0.20	0.54	0.98
steken	0.97	Uni	0.07	0.93	4.70	0.17	4.70	3.64
stempelen	1.00	Uni	0.10	0.90	3.79	0.25	3.79	4.08
stofzuigen	1.00	Bi	0.97	0.03	0.14	0.09	0.21	1.90
stoten	0.97	Uni	0.45	0.55	1.23	0.47	1.95	1.89
strelen	1.00	Uni	0.24	0.76	3.93	0.41	4.38	2.59
strijken	0.97	Bi	0.62	0.38	3.80	0.24	3.80	3.97
strooien	1.00	Uni	0.21	0.79	4.28	0.23	4.28	3.74
sturen	0.87	Bi	0.86	0.14	0.56	0.28	0.56	0.89
tekenen	1.00	Uni	0.21	0.79	4.07	0.22	4.07	4.89
tikken	1.00	Uni	0.14	0.86	4.07	0.43	4.41	3.04
tillen	1.00	Bi	1.00	0.00	0.00	0.00	0.00	0.71
timmeren	1.00	Bi	0.93	0.07	2.81	0.22	2.81	3.28
toesteken	0.90	Uni	0.28	0.72	3.29	0.43	3.29	2.59
tokkelen	0.97	Bi	0.66	0.34	0.70	0.38	1.02	1.44
tossen	0.61	Uni	0.25	0.75	2.91	0.60	3.44	3.75
trekken	1.00	Bi	0.83	0.17	1.26	0.39	1.29	2.01
typen	1.00	Bi	1.00	0.00	0.16	0.08	0.16	0.86
uitgommen	1.00	Uni	0.28	0.72	3.83	0.24	3.83	4.48
uitkleden	1.00	Bi	1.00	0.00	0.10	0.05	0.14	0.86
uitpersen	0.97	Bi	0.79	0.21	2.30	0.27	2.30	2.82
uitschenken	1.00	Uni	0.34	0.66	3.69	0.22	3.69	3.97
uitscheppen	1.00	Uni	0.38	0.62	2.69	0.30	2.69	3.74

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
uitsmeren	1.00	Uni	0.45	0.55	3.59	0.26	3.59	3.56
uitspreiden	0.84	Bi	0.70	0.30	0.85	0.30	0.85	1.17
uitsteken	0.77	Uni	0.29	0.71	3.55	0.43	3.55	2.78
uitwissen	1.00	Uni	0.21	0.79	4.36	0.18	4.36	3.75
uitwringen	1.00	Bi	1.00	0.00	0.19	0.07	0.22	0.80
vangen	0.97	Bi	0.89	0.11	0.48	0.26	0.48	1.01
vastbinden	0.94	Bi	1.00	0.00	1.23	0.20	1.31	1.49
vastgespen	0.94	Bi	0.90	0.10	1.65	0.28	1.65	2.36
vastgrijpen	0.97	Bi	0.79	0.21	1.50	0.43	1.50	1.78
vasthaken	1.00	Bi	0.71	0.29	2.02	0.47	2.48	2.80
vasthouden	1.00	Bi	0.83	0.17	0.52	0.26	0.55	0.92
vastketenen	0.94	Bi	1.00	0.00	0.93	0.19	1.00	1.43
vastknopen	1.00	Bi	1.00	0.00	0.73	0.18	0.80	2.01
vastmaken	0.87	Bi	1.00	0.00	1.26	0.30	1.30	1.72
vastpakken	0.97	Bi	0.79	0.21	1.18	0.39	1.18	0.98
vastspijkeren	0.97	Bi	0.86	0.14	2.28	0.16	2.28	3.22
vergrendelen	0.94	Bi	0.62	0.38	3.09	0.32	3.24	3.28
verkreukelen	0.97	Bi	1.00	0.00	0.32	0.12	0.32	0.77
vermalen	0.84	Bi	0.65	0.35	2.50	0.30	2.50	2.75
verpletteren	0.97	Bi	0.61	0.39	1.41	0.41	1.77	2.22
verscheuren	1.00	Bi	1.00	0.00	0.59	0.13	0.59	0.86
verven	1.00	Uni	0.31	0.69	4.40	0.23	4.40	4.31
verzamelen	0.90	Bi	0.96	0.04	0.71	0.20	0.79	1.48
voelen	0.97	Bi	0.76	0.24	1.68	0.51	2.39	1.44

Table 6.1, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
vouwen	1.00	Bi	1.00	0.00	0.98	0.17	0.98	1.38
wassen	0.94	Bi	0.83	0.17	1.11	0.30	1.19	2.07
wegjagen	1.00	Bi	0.92	0.08	0.93	0.36	0.93	0.49
wegslingeren	0.97	Uni	0.45	0.55	3.18	0.36	3.18	3.28
werpen	1.00	Uni	0.10	0.90	3.67	0.31	3.67	4.20
weven	0.77	Bi	1.00	0.00	1.75	0.31	1.75	1.61
worstelen	0.87	Bi	0.96	0.04	0.26	0.16	0.26	0.71
wrijven	1.00	Uni	0.45	0.55	2.64	0.37	2.64	2.13
wuiven	1.00	Uni	0.03	0.97	4.81	0.17	4.81	4.02
wurgen	1.00	Bi	0.97	0.03	0.17	0.18	0.28	0.52
zagen	1.00	Bi	0.76	0.24	3.21	0.21	3.21	4.08
zwaaien	1.00	Uni	0.03	0.97	4.81	0.17	4.81	3.97
zwabberen	0.71	Bi	0.91	0.09	0.39	0.23	0.39	1.96

Table 6.2: English Item-wise statistics. % Accuracy based on pantomime data. Max.Cat.: Category label maximally assigned. Impl. Uni.: Average Implicit Unimanuality. Expl.Cont: Explicit Continuous Rating transformed. See Analysis section for information on how these variables were calculated.

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
applaud	1.00	Bi	1.00	0.00	0.00	0.10	0.20	0.58
armwrestle	1.00	Uni	0.04	0.96	3.90	0.38	3.90	4.87
autograph	1.00	Uni	0.08	0.92	3.92	0.25	3.92	5.00
bang	0.95	Uni	0.35	0.65	2.68	0.84	4.26	3.21
bash	0.95	Bi	0.64	0.36	2.05	0.50	2.05	2.47
beat	1.00	Bi	0.65	0.35	2.38	0.43	2.38	1.92
bind	1.00	Bi	0.92	0.08	0.05	0.20	0.55	1.67
blindfold	1.00	Bi	0.96	0.04	0.00	0.00	0.00	1.27
blot	1.00	Uni	0.08	0.92	4.15	0.24	4.15	3.33
bowl	0.82	Uni	0.08	0.92	4.19	0.19	4.19	4.73
box	1.00	Bi	1.00	0.00	0.30	0.16	0.40	1.35
braid	1.00	Bi	1.00	0.00	0.02	0.02	0.02	0.71
broom	0.95	Bi	0.96	0.04	0.18	0.14	0.18	1.86
brush	1.00	Uni	0.12	0.88	3.73	0.68	4.72	3.33
buckle	0.95	Bi	0.88	0.12	0.97	0.49	1.55	2.50
bury	1.00	Bi	1.00	0.00	0.22	0.16	0.32	1.99
butter	1.00	Uni	0.38	0.62	2.90	0.14	2.90	3.53
button	1.00	Bi	0.92	0.08	0.25	0.19	0.50	1.99
capture	0.86	Bi	0.92	0.08	0.56	0.31	0.56	1.35
caress	0.91	Bi	0.64	0.36	2.38	0.80	3.50	1.27
carry	1.00	Bi	0.96	0.04	0.08	0.08	0.08	1.03
carve	0.95	Uni	0.46	0.54	2.84	0.20	2.84	3.65

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
catch	1.00	Bi	0.54	0.46	0.88	0.55	1.38	2.56
chain	0.86	Bi	0.73	0.27	0.58	0.23	0.58	1.92
chisel	0.95	Bi	0.54	0.46	1.71	0.34	2.18	3.46
chop	1.00	Bi	0.52	0.48	3.27	0.39	3.58	4.07
chuck	0.91	Uni	0.15	0.85	3.95	0.52	4.47	3.72
clap	1.00	Bi	0.96	0.04	-0.15	0.13	0.15	0.06
clasp	1.00	Bi	0.69	0.31	1.02	0.42	1.02	1.79
cleave	0.68	Bi	0.52	0.48	2.40	0.56	2.40	3.07
cling	0.91	Bi	0.85	0.15	0.66	0.33	0.66	1.15
clobber	0.95	Bi	0.81	0.19	1.21	0.43	1.21	1.92
club	0.86	Bi	0.50	0.50	0.86	0.40	0.86	3.40
clutch	1.00	Bi	0.73	0.27	1.57	0.50	1.57	1.60
color	1.00	Uni	0.23	0.77	4.05	0.22	4.05	4.42
comb	1.00	Uni	0.27	0.73	2.17	0.80	3.67	3.27
crochet	0.86	Bi	0.92	0.08	1.71	0.26	1.71	2.00
crumple	0.95	Bi	0.88	0.12	0.03	0.03	0.03	1.03
crush	0.95	Bi	0.54	0.46	1.62	0.36	1.62	2.50
cuddle	1.00	Bi	0.92	0.08	0.20	0.20	0.20	0.32
cut	1.00	Uni	0.27	0.73	3.90	0.45	4.25	4.10
dab	0.68	Uni	0.20	0.80	4.25	0.28	4.25	2.93
dial	1.00	Uni	0.12	0.88	3.30	0.41	3.60	4.10
dice	0.95	Bi	0.56	0.44	2.70	0.37	3.00	3.60
dig	1.00	Bi	0.92	0.08	0.62	0.32	0.68	1.54
dissect	1.00	Bi	0.88	0.12	1.18	0.20	1.18	2.82

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
doodle	1.00	Uni	0.12	0.88	4.17	0.23	4.17	4.62
drag	0.95	Bi	0.88	0.12	0.47	0.33	0.47	1.53
draw	1.00	Uni	0.08	0.92	3.85	0.24	3.85	4.68
drill	0.95	Bi	0.69	0.31	2.12	0.45	2.42	3.14
drum	1.00	Bi	1.00	0.00	0.05	0.03	0.05	0.83
dunk	1.00	Bi	0.62	0.38	1.45	0.57	1.95	2.12
dust	1.00	Uni	0.35	0.65	3.70	0.50	4.20	3.27
embrace	1.00	Bi	1.00	0.00	0.00	0.00	0.00	0.26
embroider	0.91	Bi	0.65	0.35	2.11	0.22	2.11	2.82
engrave	0.95	Uni	0.23	0.77	3.58	0.28	3.58	4.29
erase	1.00	Uni	0.15	0.85	3.80	0.29	3.80	3.72
etch	0.77	Uni	0.08	0.92	3.50	0.44	3.50	4.10
fasten	0.95	Bi	0.92	0.08	0.62	0.37	1.07	2.12
fence	0.91	Uni	0.19	0.81	4.36	0.24	4.36	4.29
fiddle	0.91	Bi	0.85	0.15	0.78	0.35	1.00	2.18
fish	1.00	Bi	0.92	0.08	0.70	0.25	1.05	2.37
flatten	1.00	Bi	0.92	0.08	0.65	0.21	0.65	1.20
flick	1.00	Uni	0.04	0.96	3.90	0.69	4.90	3.46
fling	1.00	Uni	0.12	0.88	4.20	0.34	4.20	3.67
flog	0.68	Uni	0.16	0.84	3.13	0.57	3.13	3.47
floss	1.00	Bi	0.88	0.12	0.05	0.05	0.05	1.39
fold	1.00	Bi	0.96	0.04	0.88	0.33	0.92	1.15
fondle	0.91	Bi	0.88	0.12	1.16	0.71	2.21	1.15
frisk	0.82	Bi	0.80	0.20	0.31	0.31	0.31	1.40

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
gather	0.95	Bi	1.00	0.00	0.24	0.14	0.24	0.90
gesture	1.00	Bi	0.54	0.46	1.52	0.70	2.52	1.99
glue	1.00	Bi	0.54	0.46	1.85	0.45	2.35	3.53
gouge	0.86	Uni	0.28	0.72	2.50	0.78	3.61	3.27
grab	1.00	Uni	0.31	0.69	1.50	0.97	4.00	2.82
grasp	1.00	Bi	0.56	0.44	2.25	0.71	3.25	1.87
grate	0.91	Bi	0.81	0.19	1.94	0.25	2.17	3.33
grease	0.82	Bi	0.50	0.50	3.06	0.31	3.06	3.27
grind	0.95	Bi	0.68	0.32	2.38	0.30	2.38	2.73
grip	1.00	Bi	0.69	0.31	1.92	0.61	2.42	1.86
grope	0.91	Bi	0.81	0.19	1.14	0.50	1.14	1.79
hammer	1.00	Uni	0.24	0.76	3.23	0.33	3.23	4.20
hand	1.00	Uni	0.08	0.92	2.98	0.64	3.42	3.40
handcuff	0.95	Bi	0.88	0.12	0.48	0.24	0.48	1.86
handle	0.77	Bi	0.79	0.21	1.00	0.50	1.00	1.46
hang	1.00	Bi	0.62	0.38	1.92	0.49	1.92	2.12
haul	0.91	Bi	1.00	0.00	0.03	0.03	0.03	0.96
hit	1.00	Uni	0.15	0.85	4.12	0.27	4.12	3.65
hoe	0.82	Bi	0.92	0.08	0.50	0.30	0.50	1.99
hoist	0.86	Bi	0.96	0.04	0.11	0.11	0.11	0.87
hold	1.00	Bi	0.73	0.27	1.35	0.48	1.45	1.09
hug	1.00	Bi	1.00	0.00	0.12	0.12	0.12	0.27
initial	0.95	Uni	0.00	1.00	4.39	0.22	4.39	4.80
inject	1.00	Uni	0.32	0.68	2.70	0.44	3.20	4.13

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
inscribe	0.86	Uni	0.16	0.84	3.88	0.27	3.88	4.27
iron	1.00	Uni	0.42	0.58	3.27	0.50	3.77	4.17
jab	1.00	Uni	0.12	0.88	3.70	0.67	4.65	3.53
juggle	1.00	Bi	1.00	0.00	0.00	0.00	0.00	0.32
knead	0.95	Bi	0.96	0.04	0.57	0.22	0.57	0.51
knit	1.00	Bi	0.96	0.04	0.75	0.22	0.75	1.35
knock	1.00	Uni	0.08	0.92	5.00	0.00	5.00	3.80
ladle	0.86	Uni	0.04	0.96	3.50	0.57	4.06	4.20
lift	1.00	Bi	0.92	0.08	0.00	0.00	0.00	1.15
lock	1.00	Uni	0.27	0.73	3.52	0.35	3.52	4.36
loosen	0.91	Bi	0.73	0.27	0.63	0.26	0.84	1.67
lug	0.86	Bi	1.00	0.00	0.22	0.29	0.33	1.27
mash	1.00	Uni	0.46	0.54	2.85	0.47	3.15	2.44
massage	1.00	Bi	1.00	0.00	0.32	0.19	0.32	0.71
measure	1.00	Bi	0.96	0.04	0.50	0.20	0.70	2.24
mend	0.86	Bi	0.80	0.20	1.44	0.26	1.44	3.00
milk	0.91	Bi	0.92	0.08	0.53	0.31	0.53	0.67
mince	0.86	Uni	0.46	0.54	3.09	0.19	3.09	4.03
mix	1.00	Uni	0.42	0.58	2.73	0.35	2.73	3.33
mold	0.95	Bi	1.00	0.00	0.21	0.16	0.37	1.35
mop	1.00	Bi	0.96	0.04	0.08	0.05	0.08	1.54
mow	1.00	Bi	0.92	0.08	-0.08	0.08	0.08	0.53
nail	1.00	Bi	0.50	0.50	2.42	0.43	2.92	3.40
nudge	1.00	Uni	0.08	0.92	0.88	1.05	4.38	1.99

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
pack	1.00	Bi	1.00	0.00	0.52	0.18	0.62	1.41
paddle	0.95	Bi	0.80	0.20	0.45	0.31	0.45	1.27
paint	1.00	Uni	0.15	0.85	4.40	0.21	4.40	4.42
pat	0.95	Uni	0.08	0.92	3.50	0.75	4.75	2.76
peel	1.00	Bi	0.73	0.27	1.43	0.39	2.08	3.33
pen	0.95	Uni	0.04	0.96	3.92	0.23	3.92	4.55
pet	1.00	Uni	0.31	0.69	3.33	0.69	4.38	1.79
photograph	1.00	Bi	0.88	0.12	0.95	0.05	0.95	2.50
pick	1.00	Uni	0.23	0.77	3.70	0.58	4.20	2.76
pierce	1.00	Uni	0.19	0.81	2.90	0.39	2.95	3.78
pinch	1.00	Uni	0.08	0.92	3.75	0.50	4.25	2.88
place	0.95	Uni	0.46	0.54	-0.08	0.60	1.50	2.88
plant	1.00	Bi	0.92	0.08	1.15	0.38	1.32	1.87
pluck	1.00	Uni	0.15	0.85	4.03	0.53	4.53	3.97
plug	0.95	Uni	0.12	0.88	4.05	0.26	4.05	3.08
point	1.00	Uni	0.00	1.00	3.50	0.82	5.00	3.21
poke	1.00	Uni	0.08	0.92	4.50	0.50	5.00	3.65
polish	1.00	Uni	0.46	0.54	3.88	0.30	3.88	3.21
pound	1.00	Bi	0.65	0.35	2.75	0.37	2.75	1.99
pour	1.00	Uni	0.35	0.65	3.27	0.34	3.27	3.91
press	1.00	Uni	0.46	0.54	2.60	0.48	2.70	3.01
prod	0.86	Uni	0.00	1.00	3.86	0.70	4.81	3.03
prune	0.77	Bi	0.62	0.38	3.40	0.38	3.40	2.78
pull	1.00	Bi	0.88	0.12	1.25	0.62	1.75	1.99

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
pulverize	0.95	Bi	0.84	0.16	1.87	0.41	1.87	1.93
pummel	0.86	Bi	0.88	0.12	0.58	0.29	0.58	1.60
punch	1.00	Uni	0.15	0.85	4.30	0.21	4.30	3.65
push	1.00	Bi	0.92	0.08	0.00	0.00	0.00	0.45
raise	1.00	Bi	0.65	0.35	0.00	0.36	0.50	1.41
rake	1.00	Bi	0.96	0.04	0.00	0.22	0.30	2.12
rattle	0.95	Uni	0.46	0.54	2.62	0.56	2.62	1.99
reach	1.00	Bi	0.50	0.50	0.55	1.01	4.00	2.24
rip	1.00	Bi	1.00	0.00	0.22	0.15	0.32	1.60
row	1.00	Bi	0.96	0.04	0.00	0.00	0.00	0.51
rub	1.00	Uni	0.46	0.54	2.88	0.44	2.92	1.73
rummage	1.00	Bi	0.96	0.04	0.28	0.25	0.28	1.09
salute	1.00	Uni	0.04	0.96	5.00	0.00	5.00	4.62
saw	1.00	Bi	0.58	0.42	2.92	0.52	3.42	3.78
scoop	1.00	Uni	0.15	0.85	4.05	0.29	4.05	3.78
scrape	0.95	Uni	0.23	0.77	3.97	0.28	3.97	3.59
scratch	0.95	Uni	0.24	0.76	3.10	0.55	3.60	2.07
scrawl	0.73	Uni	0.23	0.77	4.34	0.25	4.34	4.42
scribble	1.00	Uni	0.12	0.88	4.30	0.22	4.30	4.49
scrub	1.00	Uni	0.46	0.54	3.52	0.31	3.52	3.01
sculpt	0.91	Bi	0.84	0.16	0.79	0.33	0.79	2.47
seize	0.86	Bi	0.80	0.20	0.94	0.62	1.53	1.20
sew	1.00	Bi	0.69	0.31	2.52	0.22	2.52	3.65
shake	1.00	Bi	0.58	0.42	1.70	0.53	1.70	2.08

Table 6.2, continued

Word	**%** **Accuracy**	**Max** **Cat.**	**%** **Bi**	**%** **Uni**	**Mean** **RHD**	**SE** **RHD**	**Impl.** **Uni.**	**Expl.** **Cont.**
sharpen	0.95	Bi	0.58	0.42	1.82	0.43	2.45	3.53
shave	1.00	Uni	0.27	0.73	4.32	0.53	4.84	4.23
shear	0.77	Bi	0.60	0.40	2.81	0.50	3.19	2.67
shoo	1.00	Uni	0.35	0.65	2.12	0.75	3.12	1.54
shoot	1.00	Bi	0.77	0.23	2.12	0.51	2.12	2.63
shove	1.00	Bi	0.92	0.08	0.00	0.00	0.00	0.96
shovel	1.00	Bi	0.96	0.04	0.18	0.08	0.18	1.99
shred	0.91	Bi	0.85	0.15	0.66	0.24	0.71	1.54
shut	1.00	Uni	0.15	0.85	3.40	0.44	3.40	2.44
sign	0.95	Uni	0.08	0.92	3.77	0.35	3.77	4.62
sketch	1.00	Uni	0.12	0.88	3.65	0.23	3.65	4.74
skewer	0.86	Bi	0.60	0.40	1.39	0.63	2.72	3.00
slam	0.95	Uni	0.31	0.69	3.33	0.49	3.33	3.14
slap	1.00	Uni	0.04	0.96	4.70	0.16	4.70	3.78
slash	1.00	Uni	0.12	0.88	4.45	0.34	4.45	4.07
slice	1.00	Uni	0.46	0.54	3.35	0.26	3.35	4.04
sling	0.86	Uni	0.42	0.58	1.75	0.70	2.38	2.31
slit	0.95	Uni	0.23	0.77	3.76	0.42	4.03	3.65
smack	1.00	Uni	0.08	0.92	3.90	0.55	4.40	3.53
smash	1.00	Bi	0.69	0.31	1.73	0.43	1.73	2.24
smear	1.00	Uni	0.24	0.76	4.00	0.35	4.00	2.47
smooth	1.00	Bi	0.69	0.31	2.35	0.43	2.45	1.47
smudge	1.00	Uni	0.12	0.88	4.05	0.22	4.05	2.76
snap	0.95	Bi	0.50	0.50	2.00	0.67	2.50	1.73

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
snatch	1.00	Uni	0.27	0.73	1.60	0.90	3.65	2.82
snip	1.00	Uni	0.20	0.80	4.17	0.24	4.17	4.33
soap	1.00	Bi	0.69	0.31	1.65	0.41	1.70	2.05
spank	0.95	Uni	0.08	0.92	3.97	0.29	3.97	4.10
spar	0.86	Bi	0.69	0.31	2.25	0.49	2.31	2.69
spear	1.00	Uni	0.48	0.52	2.58	0.63	3.08	3.27
spread	1.00	Uni	0.40	0.60	2.03	0.38	2.03	3.07
sprinkle	1.00	Uni	0.23	0.77	4.10	0.55	4.60	3.01
squeeze	1.00	Bi	0.73	0.27	0.40	0.28	0.40	1.47
stab	1.00	Uni	0.04	0.96	4.05	0.51	4.55	4.36
stack	1.00	Bi	0.96	0.04	0.00	0.00	0.00	1.15
staple	1.00	Uni	0.15	0.85	2.65	0.41	2.95	3.08
steer	1.00	Bi	1.00	0.00	0.28	0.25	0.28	1.00
stir	1.00	Uni	0.31	0.69	3.85	0.39	3.85	3.85
stitch	0.95	Bi	0.69	0.31	2.90	0.24	2.90	3.27
strangle	1.00	Bi	0.96	0.04	0.00	0.00	0.00	0.83
strap	1.00	Bi	0.96	0.04	0.80	0.48	1.45	1.73
strike	1.00	Uni	0.12	0.88	3.65	0.37	3.65	3.85
stroke	1.00	Uni	0.23	0.77	3.58	0.63	4.33	2.69
strum	0.95	Uni	0.35	0.65	1.63	0.26	1.95	3.97
stuff	1.00	Bi	0.92	0.08	1.65	0.28	1.85	1.80
swab	0.91	Uni	0.08	0.92	3.89	0.49	4.21	3.40
swaddle	0.68	Bi	0.92	0.08	0.32	0.19	0.32	0.93
swat	1.00	Uni	0.12	0.88	5.00	0.00	5.00	3.33

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
sweep	1.00	Bi	0.96	0.04	0.12	0.10	0.12	1.81
switch	0.95	Uni	0.44	0.56	0.56	0.77	2.22	1.47
text	1.00	Bi	0.92	0.08	0.00	0.00	0.00	1.47
throw	1.00	Uni	0.08	0.92	4.40	0.16	4.40	3.33
thumb	0.77	Uni	0.20	0.80	3.12	0.84	4.31	3.33
tickle	0.95	Bi	0.92	0.08	1.50	0.53	1.50	1.03
tie	1.00	Bi	0.92	0.08	0.05	0.07	0.11	1.79
tinker	0.82	Bi	0.92	0.08	0.94	0.41	1.06	0.97
tip	0.91	Uni	0.27	0.73	1.26	0.67	2.09	2.69
toss	1.00	Uni	0.12	0.88	3.92	0.58	4.42	3.97
touch	1.00	Bi	0.50	0.50	4.10	0.42	4.40	1.99
trace	1.00	Uni	0.15	0.85	4.00	0.24	4.00	4.29
tug	1.00	Bi	0.69	0.31	1.50	0.53	1.50	2.37
twiddle	0.82	Bi	0.88	0.12	0.29	0.29	0.29	0.38
twist	1.00	Bi	0.88	0.12	0.55	0.24	0.55	1.03
type	1.00	Bi	1.00	0.00	0.00	0.00	0.00	0.51
unclog	0.73	Bi	0.69	0.31	1.69	0.42	1.94	2.56
uncork	1.00	Bi	0.77	0.23	1.98	0.24	2.12	3.46
underline	1.00	Uni	0.12	0.88	4.20	0.22	4.20	4.68
undress	1.00	Bi	1.00	0.00	0.12	0.08	0.12	0.64
unravel	0.95	Bi	0.85	0.15	1.66	0.38	1.76	1.60
unscrew	1.00	Bi	0.54	0.46	2.50	0.31	2.50	3.40
untie	0.95	Bi	0.92	0.08	0.11	0.10	0.16	1.47
unwrap	1.00	Bi	0.96	0.04	0.45	0.26	0.45	1.28

Table 6.2, continued

Word	**% Accuracy**	**Max Cat.**	**% Bi**	**% Uni**	**Mean RHD**	**SE RHD**	**Impl. Uni.**	**Expl. Cont.**
vacuum	1.00	Bi	0.54	0.46	2.08	0.53	2.23	2.56
wash	1.00	Bi	1.00	0.00	1.65	0.35	1.65	1.60
wave	1.00	Uni	0.12	0.88	4.25	0.55	4.75	3.53
weave	0.91	Bi	0.84	0.16	1.18	0.39	1.52	2.00
whack	1.00	Uni	0.12	0.88	3.33	0.61	3.83	3.46
whip	1.00	Uni	0.12	0.88	3.98	0.40	3.98	4.29
wipe	1.00	Uni	0.23	0.77	4.85	0.11	4.85	3.14
wrap	0.95	Bi	1.00	0.00	0.71	0.24	0.71	1.73
wrench	0.91	Uni	0.40	0.60	2.82	0.47	2.82	3.40
wring	0.91	Bi	0.96	0.04	0.00	0.00	0.00	0.83
write	1.00	Uni	0.08	0.92	4.03	0.23	4.03	4.87
yank	1.00	Uni	0.46	0.54	2.25	0.68	2.75	2.95