Simulating Semantics:

Are Individual Differences in Motor Imagery Related to Sensorimotor Effects in Language Processing?

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Abstract

In embodied theories of semantic representation, the processes and mechanisms of modal simulations that are engaged during semantic processing have tended to be under-specified. We investigated the possibility that motor imagery may be a mechanism of simulation, using an individual differences approach. In this pre-registered study, we assessed motor imagery abilities ($n = 161$) with implicit and explicit measures and identified two latent factors. We then examined whether those factors account for significant variations in sensorimotor effects observed in three different language tasks: a lexical decision task, syntactic classification task, and sentence-picture verification task. In the language tasks, when all participants were considered together, we replicated some previously reported sensorimotor effects (e.g., body-object interaction, BOI, effects in semantic processing, wherein words associated with more sensorimotor information were processed more quickly than words associated with less sensorimotor information) and did not replicate others (e.g., BOI effects in the LDT, congruency effects in SPVT). There were no significant relationships between imagery factor scores and sensorimotor effects. A follow-up analysis using scores from each motor imagery measure revealed a significant interaction between hand movement imagery and BOI effects in the syntactic classification task, with those higher in this imagery ability showing a larger BOI effect. This latter result may suggest that specific types of motor imagery are related to sensorimotor effects in semantic processing, however further investigation is needed. In general, our findings provide little support for the possibility that motor imagery is an underlying mechanism of sensorimotor simulation during language processing.

Keywords: Semantic Representation, Embodied Cognition, Motor Imagery, Sentence-Picture Verification, Lexical-Semantic Processing

Simulating Semantics: Are Individual Differences in Motor Imagery Related to Sensorimotor Effects in Language Processing?

The process by which word meaning is represented and accessed is highly complex and still not fully understood. Theories that explain this process have evolved from purely amodal semantic processing based on symbolic representations (Pylyshyn, 1980) to embodied semantic processing that is reliant on perceptual, motor and emotional simulations (Glenberg & Gallese, 2012). Several current theoretical positions have found a middle ground between purely amodal and purely modal semantic representations, proposing that concepts have flexible, multi-modal representations that rely on a variety of sensorimotor, linguistic and introspective grounding, dependent on the type of word and the context in which those words are processed (Barsalou et al., 2008; Barsalou, 2016; Borghi et al., 2017; Louwerse, 2011).

Fundamental to nearly all but the amodal accounts of semantic representation is the proposal that mental simulations are engaged during semantic retrieval. In most accounts, simulation of sensorimotor experience (e.g., motor, visual, haptic, etc.) is automatically engaged when a word's meaning is processed (Barsalou, 2008). Simulations involve re-enacting perceptual-motor experiences without sensory input or physical experience, but the nature of simulation tends to be underspecified in most theories of embodied semantic representation. One proposal is that simulation occurs via neural reuse, wherein simulations partially engage sensorimotor regions of the brain that are engaged during perception and action (Barsalou, 2016). However, this neural reuse account lacks specificity on exactly *how* neural reuse occurs. For instance, questions remain as to which regions are shared between sensorimotor simulations and perception and action, and whether these shared neural pathways are used in the same manner for these different processes (Barsalou, 2016). One possibility is that simulation is akin to a form of mental imagery, which is defined as a representation created through perceptual processes in the absence of a stimulus being perceived (Kosslyn et al., 2006).

Mental imagery can engage multiple sensory modalities, but the most commonly investigated modalities are visual and motor. Both visual and motor imagery correspond to modal simulations said to be recruited as part of semantic representation, however most previous research has focused on the relationship between visual imagery and semantic processing. In the present study we investigated the possibility that motor imagery is analogous to the mental simulations used in semantic representation and implicated in language processing. To do so, we assessed individual differences in motor imagery, and investigated whether those individual differences are related to sensorimotor effects in language processing. In what follows we will outline evidence of sensorimotor simulation in semantic representation, describe the construct of motor imagery, and consider the role of individual differences in reconciling theoretical debates in language processing.

Simulation in Semantic Representation

The embodied (or grounded) cognition framework proposes a central role for simulated sensorimotor experience in explaining semantic representation (Pecher & Zwaan, 2005). Early explorations of embodied semantic representation provided evidence of motor simulations during language processing. For example, neuroimaging studies showed that when participants read concrete action words related to effector-specific areas (e.g., *kick: leg*, *lick: mouth*, etc.) activation was observed in the corresponding somatotopic regions of the motor and premotor cortex (Hauk et al., 2004) and transcranial magnetic stimulation (TMS) to effector-specific motor areas has been associated with faster responses on lexical decision tasks (LDT) for motor words (e.g., TMS to the arm area caused faster responses to arm-related words; Pulvermüller et al., 2005).

Behavioural studies have also demonstrated sensorimotor effects in language processing. Processing is typically faster for words high in body-object interaction (BOI; the ease with which the human body can interact with a word's referent; Siakaluk et al., 2008) than for words low in BOI, for instance in the LDT (Bennett et al., 2011) and the syntactic classification task (SCT; Tousignant &

Pexman, 2012). Lynott et al. (2020) found that composite variables of perceptual and action strength accounted for significant variance in both response times and accuracy in the LDT. Similarly, sensory experience ratings (SER; the amount of sensory and/or perceptual experience associated with a word's referent) account for significant variance in LDT response times, with words higher in SER being processed more quickly (Juhasz et al., 2011, Juhasz & Yap, 2013). It is proposed that these sensorimotor effects reflect simulation of sensorimotor experience when these words are processed.

Embodied effects have also been observed in sentence processing, often in the sentence picture verification task (SPVT). In this task, image recognition is slower for object images that are incongruent with the orientation, color, or shape of that same object described in a sentence preceding the image (Stanfield & Zwaan, 2001; Zwaan & Pecher, 2012). It is proposed that reading the sentence activates a mental simulation. Responses to images that are incongruent with the sentence description are slower due to a switching cost from the mental simulation generated during sentence processing to the orientation, color, or shape details conveyed in the presented image.

Mental Imagery

Mental imagery has been the subject of debate about whether it is epiphenomenal in relation to cognitive processes and concerns have been raised over how imagery can be empirically evaluated (Kosslyn et al., 2006; Pearson & Kosslyn, 2015). However, the greatest debate has centered on the actual content of mental imagery (Anderson, 1978; Kosslyn & Pomerantz, 1977; Pylyshyn, 1973), with questions as to whether mental imagery is truly a representational system based on simulating sensorimotor states or whether these mental “images” are generated from amodal, propositional representations. The advancement of neuroimaging methods has helped to address this central debate; visual imagery has been linked to neural areas related to early visual processing (Kosslyn et al., 1997; Pearson et al., 2015; Slotnick et al., 2005; Stokes et al., 2009; Winlove et al., 2018) and motor imagery has shown significant overlap with neural areas associated with motor execution including the premotor

cortex, primary motor cortex and basal ganglia (Decety, et al., 1994; Gerardin et al., 2000; Porro et al., 1996; Roth et al., 1996).

Mental imagery can engage many different modalities, such as auditory, tactile, olfactory, etc. (Madan & Singhal, 2012). Motor imagery, in particular, is now an actively investigated subset of mental imagery. Traditionally, motor imagery was defined as a conscious, explicit representation of self-generated action. However, the assumption that motor imagery must by definition be a conscious activity has been challenged, and this definition has been expanded to include unconscious and/or implicit imagery (Jeannerod & Frak, 1999). Motor imagery also includes several different dimensions such as point-of-view (e.g. egocentric imagery of actions undertaken by the self vs allocentric imagery of imagining actions of others; Madan & Singhal, 2012), generation (including the ease with which imagery is generated and the vividness of said image; Dahm, 2020; Kraeutner et al., 2020), manipulability (the ability to change or modify motor imagery; Kraeutner et al., 2020), and maintenance (the ability to mentally hold motor imagery; Dahm, 2020; Kraeutner et al., 2020). These dimensions are assessed using different questionnaires and tasks. When determining motor imagery ability it is recommended that a battery of motor imagery assessments be used in order to encompass all these dimensions (Dahm, 2020; Kraeutner et al., 2020; McAvinue & Robertson, 2008).

To our knowledge, the only previous study to directly investigate the relationship between motor imagery and language processing was reported by Willems et al. (2009); they investigated neural activity during action verb processing and motor imagery, to determine whether the two processes shared neural correlates. Willems et al. found dissociations of neural activity between the language and imagery tasks: while the imagery tasks demonstrated increased activity in the pre-motor and primary motor cortex, the language task showed activity only in the pre-motor cortex, in regions distinct from those engaged during imagery. Willems et al. concluded that processes of mental simulation during language processing are distinct from processes of imagery. While their study suggests that these two

processes do not share associated neural activity patterns, the poor temporal resolution of fMRI did not allow investigation of the temporal relationship between neural activity during language processing and neural activity during imagery. Furthermore, participants' motor imagery abilities were not measured. If some participants are more adept at imagery this may alter the degree to which they employ simulations or imagery during language processing.

It has been a challenge for researchers to measure motor imagery ability at an individual level, but there are now a number of questionnaires that assess motor imagery ability through either explicit self-reported ability or through objective tests (Madan & Singhal, 2013; Ochipa et al., 1997; Roberts et al., 2008). Experimental tasks have also been developed for which responses depend on implicit motor imagery in order to provide a response. These include the mental rotation task (Shepard & Metzler, 1971) and the hand laterality task (Parsons, 1987). To date, these questionnaires and tasks have been used to investigate motor imagery in clinical and non-clinical populations, and in athlete populations for the purposes of performance enhancement, but individual differences have yet to be explored (McAvinue & Robertson, 2008).

Individual Differences

Individual differences are person-specific variations in cognitive processes or performance. They are not often the focus in cognitive research, and specifically in language processing research, and are typically relegated to a source of error or random effects in experimental designs. One particular challenge has been the lack of reliable psychometric tools to accurately measure individual differences related to language processing (Kidd et al., 2018). Nonetheless, individual differences offer potential explanations for variance typically attributed to error, for inconsistent replication of effects, and could help resolve theoretical debates in embodied cognition (Barsalou, 2020). Recently, a number of studies have reported that individual differences can account for variations in semantic effects in language processing (see Andrews et al., 2017, Pexman & Yap, 2018). These studies demonstrate that individual

differences can be meaningfully discerned within a standard undergraduate student sample and that response times in semantic decision tasks are sensitive to those individual differences.

Thus, individual differences seems a viable strategy to investigate the role that is proposed for mental imagery in language processing within the theoretical framework of embodied cognition. The few studies that have adopted this strategy have reported inconsistent results. Hirschfeld et al. (2012) investigated how individual differences in visual imagery were related to the N400 ERP component during a SPVT. They used the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973) and the habitual use of imagery scale from the Individual Difference Questionnaire (IDQ; Paivio & Harshman, 1983) as their visual imagery measures. They found that more vivid mental imagery was related to stronger congruency effects in the N400 and surmised that these differences could be explained by a tendency for individuals with more vivid self-reported imagery to represent nouns using more visual detail.

Zwaan and Pecher (2012) investigated individual differences in visual imagery in relationship to congruency effects in the SPVT and found no correlation between VVIQ scores and individual congruency effect sizes across six replication attempts. They suggested that mental imagery indexed by questionnaires like the VVIQ and the mental simulation engaged during tasks such as the SPVT are different processes, in that mental imagery self-reports measure conscious, explicit mental imagery whereas mental simulation during language processing is a largely unconscious process.

Finally, Pavan and Baggio (2012) examined differences in self-reported visual and movement imagery using the VVIQ and the VMIQ-2 in relation to a verb-phrase judgement task. They hypothesized that if language processing and imagery rely on similar visual processes, a motion aftereffect should be evident in verb phrase judgement responses. Their hypothesis was not supported and they also found no relationships between VVIQ scores, VMIQ-2 scores, and phrase judgement response times. The

authors concluded that individual differences in visual and movement imagery have no bearing on language processing and thus that language and visual processing depend on dissociated systems.

A common feature of these studies is that they primarily focused on individual differences in visual imagery and language task performance. As such, they emphasized activation of *visual* simulations. However, evidence suggests that *motor* simulations are activated in processing many types of concrete and abstract words (Bennett et al., 2011; Hauk et al., 2004; Pulvermüller et al., 2005). It would thus seem possible that the more relevant measure of individual differences could be motor imagery, rather than visual imagery, to account for variation in semantic processing. Furthermore, the only study that included a measure of movement imagery (Pavan & Baggio, 2012) used only one questionnaire (VMIQ-2), meaning that only one dimension of motor imagery (generation) was assessed. Finally, Zwaan and Pecher (2012) suggested that the mechanisms of implicit sensorimotor simulation during language processing are distinct from those measured through explicit imagery questionnaires. In order to address this claim, it would be necessary to assess imagery through both implicit and explicit tasks and questionnaires. To address these limitations, we adopted a multifaceted approach to assess motor imagery, employing multiple questionnaires and tasks to encompass several dimensions such as explicit and implicit imagery, point-of-view, generation, manipulation, and maintenance.

The Present Study

In the present study we investigated the relationships of individual differences in motor imagery ability to performance in three different language processing tasks: a lexical decision task (LDT; *is it a word or a nonword?*), a syntactic classification task (SCT; *is it a verb or a noun?*) and a sentence-picture verification task (SPVT; *was the image mentioned in the sentence?*). Performance in the LDT is influenced by lexical factors like overall familiarity of a word, how early that word is learned, and is indirectly influenced by semantic information (Pexman, 2012), whereas the SCT is more reliant on semantic information. It is generally assumed that both the LDT and SCT engage implicit mental imagery,

and that the SPVT requires more explicit engagement of mental imagery. In both the LDT and the SCT we selected stimuli that were either high or low in BOI, in order to examine how words with more or less semantic information related to the body may be processed differently depending on motor imagery ability. In the SPVT we included the orientation congruency manipulation to determine whether congruency effects were modulated by motor imagery ability.

Motor imagery ability was operationalized as a latent variable extracted from scores from explicit motor imagery questionnaires including the VMIQ-2 (Roberts et al., 2008), objective tests such as the Test of Ability in Movement Imagery (TAMI; Madan & Singhal, 2013), and the Florida Praxis Imagery Questionnaire (FPIQ; Ochipa et al., 1997), as well as implicit motor and movement imagery tasks, the hand laterality task (HLT; Parsons, 1987) and the mental rotation task (MRT; Shepard & Metzler, 1971). These questionnaires and tasks assessed several different dimensions of motor imagery including generation (VMIQ-2), manipulation (FPIQ, HLT & MRT) and maintenance (TAMI & FPIQ). Differences in language (vocabulary) ability and handedness were controlled for using the North American Adult Reading Test (NAART; Uttl, 2002), and the Edinburgh Handedness Inventory (EHI; Oldfield, 1970), respectively.

We tested the hypothesis that, if word dimensions such as BOI reflect the degree of mental simulation involved in language, then individual differences in motor imagery will interact with these effects, such that individuals with high motor imagery scores will show more sensitivity to motor (BOI) simulations in the LDT and SCT or to image congruency in the SPVT. We also examined main effects of motor imagery in the language processing tasks to determine if individual differences in motor imagery are related to language processing generally. Our hypotheses and analysis plan were preregistered on

Open Science Framework during data collection¹, prior to data analysis and hypothesis testing. Our preregistration, stimuli and data, can be found at <https://osf.io/s28ea>

Method

Participants

One hundred and sixty-one participants (143 female, M age = 19.97 years old, SD = 4.07) took part in the study. Participants were undergraduates at the University of Calgary and participated in exchange for course credit. Of the full sample, 113 participants reported that English was their first language and all participants reported being either completely fluent (n = 144), very fluent (n = 15), or somewhat fluent (n = 2). After applying exclusion criteria, 146 participants remained in the analysis (128 female, M age = 20.05, SD = 4.24). Of those that remained in the analysis, 102 reported that English was their first language and all analyzed participants reported being either completely fluent (n = 131), very fluent (n = 13) or somewhat fluent (n = 2). The target sample size was based on recommendations for sample size given the anticipated effect size and best practices in exploratory factor analysis. Schonbrodt and Perugini (2013) recommend a sample size of at least 116 in order to obtain a stable correlation of .10 with a 95% CI at a 0.20 corridor of stability width. Gignac and Szodorai (2016) indicate that correlations are rarely found to be as large as r = .50, and as such recommend adjusting interpretation of correlation magnitude to .10, .20, and .30 as small, medium and large respectively when conducting individual differences research. Given the inconsistent previous findings on the

¹ Our study was originally pre-registered before data collection. Two aspects of the plan were later updated in a second pre-registration during data collection. First, we increased the target sample size in line with recommended sample sizes for exploratory factor analysis. Second, we specified exclusion criteria for individual items in the LDT, SCT, and SPVT. The updated sections are indicated in the second pre-registration and the first pre-registration can be found at <https://osf.io/6dx4z>.

relationship between mental imagery and language processing, we chose a stable correlation value of .10 to inform the selection of sample size. Our analysis plan included an exploratory factor analysis, for which a target sample size of up to 200 is often considered appropriate (Howard, 2016; MacCallum et al., 1999). We intended that the sample would meet this higher recommendation; however, before we were able to achieve the full sample we had to cease data collection due to social distancing measures implemented at our institution because of the COVID-19 pandemic. Although a sample size of up to 200 is often recommended for exploratory factor analysis, there is evidence that, for simple structure factor solutions with a small number of factors, small samples are sufficient to achieve satisfactory factor extraction (de Winter et al., 2009), and this has been demonstrated in previous work on motor imagery (Madan & Singhal, 2013). Thus, on balance we considered the present sample size adequate to test our research questions. We also conducted follow up analyses to assess the relationships between imagery measures and language processing performance that do not depend on the exploratory factor analysis.

Materials

Lexical Decision Task

The LDT stimuli were 100 words and 100 nonwords. The LDT word stimuli were 50 high BOI nouns and 50 low BOI nouns (Pexman et al., 2019). These two word groups were matched ($p > .05$) on key dimensions known to influence response times such as length, frequency (log subtitle frequency; Brysbaert & New, 2009), prevalence (the number of people who know a word; Brysbaert et al., 2019), orthographic Levenshtein distance (OLD; a measure of the minimum number of letter substitutions, insertions or deletions to change one word to another; Yarkoni et al., 2008), age of acquisition (AoA; the estimated age when a word is acquired; Kuperman et al., 2012), imageability (the degree to which a word can arouse a mental image; Cortese & Fugett, 2004; Schock et al., 2012) and concreteness (the degree to which you can experience a word's referent through one of the five senses; Brysbaert et al.,

2014). Refer to Table 1 for descriptive statistics of the stimuli. Nonwords for the LDT were constructed using a pseudoword generator (Keuleers & Brysbaert, 2010) and matched to the LDT word stimuli in sub-syllabic structure and bigram frequency.

The stimuli were presented in 24-point Times New Roman font in black letters on a white background using Eprime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Each trial began with a blank screen for 500 ms, followed by a fixation cross for 500 ms and then a word replaced the fixation cross, remaining on the screen for 3,000 ms or until the participant made a response. Participants were asked to respond as quickly and accurately as possible. They received 10 practice trials with feedback prior to beginning the task and were offered a break at the halfway point (i.e., after 100 trials). Participants were instructed to look at each presented string of letters and indicate if it was a word or a nonword by making a response on the keyboard. Response buttons were “k” and “d” and were counterbalanced across participants (e.g., “k” to words for half of the participants, “k” to nonwords for the other half). All stimuli were presented in a different random order to each participant.

Syntactic Classification Task

The SCT stimuli were 100 nouns and 100 verbs. None of these words were presented in the LDT. The SCT noun stimuli were 50 high BOI nouns and 50 low BOI nouns (see Table 1 for descriptive statistics). High and low BOI nouns were matched ($p > .05$) on length, frequency, prevalence, OLD, AoA, concreteness and imageability. Verbs were included to provide negative exemplars, as the task used a go/no-go design with the prompt "is it a noun?". In previous studies using the SCT we have found that task framing is important for the effects observed (e.g., Tousignant & Pexman, 2012); since our focus was on an effect for noun stimuli, we chose a go/no-go design with a noun decision to encourage participants to emphasize noun properties. Verb stimuli were matched to both noun groups on length, frequency, prevalence, OLD, AoA, and concreteness. Verb stimuli were not matched to the nouns on

imageability or BOI due to poor availability of ratings on these dimensions for verbs, however, because verbs were "no-go" trials in this task, no behavioural data for these words were analyzed.

The SCT stimuli were presented using the same font, software and timing described for the LDT. Participants received 10 practice trials with feedback prior to beginning the task and were offered a break at the halfway point (i.e., after 100 trials). Participants were instructed to look at each presented word and respond only if the word was a noun and to do so as quickly and accurately as possible. Response buttons "k" and "d" were used, counterbalanced across participants (e.g., "k" for half of the participants, "d" for the other half). All stimuli were presented in a different random order to each participant.

Table 1

Descriptive Statistics for LDT and SCT Stimuli

Task	Word Type (n)	Length Mean <i>SD</i>	Freq Mean <i>SD</i>	OLD Mean <i>SD</i>	Prev Mean <i>SD</i>	AoA Mean <i>SD</i>	Image Mean <i>SD</i>	Conc Mean <i>SD</i>	BOI Mean <i>SD</i>
LDT	High BOI	5.46	2.61	1.97	2.20	6.76	5.62	4.36	5.58 ^a
	Nouns (50)	1.34	0.80	0.62	0.40	2.52	1.28	0.60	1.01
	Low BOI	5.46	2.70	2.00	2.25	7.14	5.62	4.23	2.39 ^a
	Nouns (50)	1.34	0.78	0.59	0.19	2.38	1.01	0.54	0.64
SCT	High BOI	5.56	2.33	2.08	2.20	8.46	5.05	4.03	5.14 ^b
	Nouns (50)	1.40	0.72	0.49	0.35	2.73	1.33	0.66	1.04
	Low BOI	5.54	2.34	2.07	2.25	7.98	5.27	3.97	2.04 ^b
	Nouns (50)	1.31	0.71	0.54	0.26	2.45	0.99	0.38	0.47
	Verbs (100)	5.67	2.15	2.03	2.19	7.86	<i>n/a</i>	3.90	<i>n/a</i>
		1.57	0.68	0.56	0.28	2.06		0.34	

Note. LDT = lexical decision task; SCT = syntactic classification task; Freq = frequency; OLD = orthographic Levenshtein distance; Prev = prevalence; AoA = age of acquisition; Image = imageability; Conc = concreteness; BOI = body-object interaction.

^a indicates that high and low BOI nouns in the LDT differ significantly on BOI ratings ($p < .001$). All other differences between LDT word types were nonsignificant ($p > .05$).

^b indicates that high and low BOI nouns in the SCT differ significantly on BOI ratings ($p < .001$). All other differences between SCT word types were nonsignificant ($p > .05$).

Sentence Picture Verification Task

The stimuli for the SPVT were adopted with very minor modification² from a set of sentence/picture stimuli originally created by Stanfield and Zwaan (2001) and shared through the Open Science Framework (<https://osf.io/2dtrh/>) as part of a replication study. A total of 78 sentences and 78 images were used in the task (48 experimental sentences and images; 24 filler sentences and images; 6 practice sentences and images). The experimental sentences consisted of 24 sentences that were designed to imply either a horizontal or vertical orientation of the object in the sentence (e.g., horizontal - "The librarian put the book back on the table"; vertical - "The librarian put the book back on the shelf"), for a total of 48 unique sentences. These sentences were paired with 24 images of objects mentioned in the sentence that were rotated to be in either a vertical or horizontal orientation (e.g., horizontal book, vertical book), for a total of 48 unique pictures.

Four experimental stimuli sets were created, with sentence-picture pairings that occurred in one of four conditions: congruent conditions (sentence vertical, image vertical; sentence horizontal, image

² The image stimuli shared through the Open Science Framework were adapted from .pic files to .bmp for use with our experimental software. Six experimental images and two filler images were not included in the Open Science Framework files. These images were sourced online to match the line drawing style of the original stimuli. One more image was replaced to better match the sentence context (e.g., a wagon wheel image was replaced with an automobile wheel image). All image stimuli used in the present study are available at: <https://osf.io/s28ea/>

horizontal) and incongruent conditions (sentence vertical, image horizontal; sentence horizontal, image vertical). An equal combination of congruent/incongruent and vertical/horizontal sentence-picture pairings were assigned to each experimental set, with a total of 24 pairings in each set. In addition to the experimental sentence-picture pairings, 24 filler sentence-picture pairings were included in each set that had a sentence (e.g., "The tour guide led his group to the top of the amphitheatre") and were matched with an image that was not mentioned in the sentence (e.g., tiger). Filler images were presented in equal numbers of horizontal and vertical orientations. For 12 of the filler pairings a comprehension question was added to encourage full reading and processing of the sentences during the task (e.g., for the previously provided sentence the comprehension question was "Where was the tour guide?"). An additional six sentence-picture pairings were used for practice prior to beginning the task; three experimental (sentence-picture pairings where the item in the image was mentioned in the sentence and the congruency of the sentence-object orientation was manipulated) and three filler (sentence-picture pairings where the item in the image was not mentioned in the sentence). One filler sentence included a comprehension question in order for participants to practice typing their responses.

The sentence stimuli were presented using 24-point Times New Roman font in black letters on a white background using Eprime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Participants were instructed to read a sentence that was presented to them. After reading the sentence, an image was presented, and they were asked to indicate if the item in the image had been mentioned in the previous sentence by pressing a button on the keyboard. Response buttons were "k" and "d" and were counterbalanced across participants (e.g., "k" to images that were mentioned in the preceding sentence for half of the participants, "k" to images that were not mentioned in the preceding sentence for the other half). Each trial began with a blank screen for 500 ms, followed by a fixation cross for 500 ms and then a sentence appeared. Participants were instructed to press the space bar once they understood the sentence. Following this response, a horizontally and vertically centered fixation cross appeared for 500

ms, followed by an image, which stayed on the screen until participants made a response. On trials with a comprehension question, the comprehension question was then presented, and participants were instructed to type their response. The question stayed on the screen until participants typed their response and pressed the enter key or until 10,000 ms had elapsed, whichever came first.

Hand Laterality Task

The stimuli for the HLT task consisted of 32 images: 16 featuring the right hand and 16 featuring the left hand. For each hand, eight images were of the palm-down view and eight were of a palm-up view, rotated from a standard anatomical position in 45° increments (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°). Consistent with previous uses of the task (Zapparoli et al., 2016) each image was presented twice, for a total of 64 trials. All images were presented in greyscale against a white background.

The image stimuli were presented on a white background using Eprime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Participants were presented with an image of a hand and asked to indicate if it was a right or left hand by pressing “k” if it was the right hand and “d” if it was the left hand. Each trial began with a blank screen for 500 ms, followed by a fixation cross for 500 ms and then the image replaced the fixation cross, remaining on the screen until the participant made a response. Participants were asked to respond as quickly and accurately as possible. They received six practice trials with feedback prior to beginning the task and image presentation order was randomized for each participant.

Mental Rotation Task

The stimuli for the MRT task consisted of 80 pairs of 3-dimensional figures; each pair included a comparison figure and a target figure. The target figure either matched the comparison figure (40 pairs) or was a mirror image of the comparison figure (40 pairs). The target figures were rotated in varying degrees of spatial orientation (between -120° to 120°, with rotations in 20° increments within this

range) along either the x, y, or z axis. All images were presented as greyscale figures against a dark background. An example of a trial image can be found on our OSF project page <https://osf.io/s28ea>

The stimuli were presented using a spatial navigation assessment tool developed by Neurolab at the University of Calgary (www.gettinglost.ca). Participants were presented with a pair of 3-dimensional figures and asked to indicate if the figure on the right was the same as the figure on the left, or if it was a mirror image of the figure on the left. If the figure was the same, they responded by pressing "1" on the keyboard and if the image was different, they responded by pressing "2". Figure pairs remained on the screen until the participant made a response.

Questionnaires

Test of Ability in Movement Imagery

The TAMI is a questionnaire designed to objectively measure imagery of whole-body movements (Madan & Singhal, 2013). The questionnaire consists of 10 questions; each question provides a sequence of five instructions, with each instruction describing a single body movement. Participants are instructed to imagine completing these movements in the order described, then asked to select an image (or other response option such as "none" or "unclear") that corresponds to the final body position that would result from completing the sequence of movements. The TAMI has high test-retest correlation, $r(19) = .71, p < .001$ and high reproducibility on mean question performance, $\rho_c(8) = .85, p < .01$ (Madan & Singhal, 2013).

Florida Praxis Imagery Questionnaire

The FPIQ is used to assess mental imagery in clinical populations, such as patients experiencing movement disorders (Ochipa et al., 1997). The questionnaire includes four subsections. Each subsection has 12 questions with two potential response options (A or B) for a total score out of 12 per subsection. The questions in the kinesthetic subsection (FPIQ Kinesthetic) ask participants to decide what joint would move the most or the least during a specified action. The questions in the position subsection

(FPIQ Position) ask participants to imagine the spatial position of the hand in relation to either an object or a body part during an action. The questions in the action subsection (FPIQ Action) ask participants to imagine the motion of a limb associated with a specific action. Finally, the questions in the object subsection (FPIQ Object) ask participants to make a judgement about an object that would be used during an action. The FPIQ has no reported psychometric evaluation, however three of the four subsections are correlated with performance on the TAMI, suggesting good concurrent validity: FPIQ Position $r = .45, p < .01$, FPIQ Action $r = .39, p < .05$, and FPIQ Object $r = .34, p < .05$. There was no significant relationship between the FPIQ Kinesthetic subscale and TAMI performance, $r = .24, p > .05$ (Madan & Singhal, 2013).

Vividness of Movement Imagery Questionnaire-2

The VMIQ-2 questionnaire is designed to assess self-reported vividness of movement imagery (Roberts et al., 2008). The questionnaire instructs a participant to imagine 12 different actions from three different viewpoints (external visual imagery, internal visual imagery, kinesthetic imagery) and then to rate the vividness of each action. Ratings are provided on a scale of 1 – 5, with 1 corresponding to images that are perfectly clear and as vivid as normal vision or feeling of movement and 5 corresponding to no image at all. Participants complete ratings for all actions from one viewpoint before moving on to the next viewpoint. Roberts et al. (2008) demonstrated good concurrent validity for the VMIQ-2, with both the internal imagery subscale ($r = -.34, p < .05$) and the external imagery subscale ($r = -.65, p < .01$) significantly correlated with the visual scale of the Movement Imagery Questionnaire Revised (MIQ-R). The kinesthetic subscale of the VMIQ-2 and the kinesthetic factor of the MIQ-R were also highly correlated ($r = -.74, p < .01$). Construct validity was also assessed by Roberts et al. by comparing differences in subscale ratings between high- and low-level athletes. They found that on all subscales high-level athletes reported more vivid imagery than low-level athletes: internal imagery $t(181.66) = -2.56, p < .01, d = .36$, external imagery $t(196) = -2.55, p < .01, d = .36$, and kinesthetic

imagery $t(186.49) = -2.87, p < .005, d = .40$. Roberts et al. also reported high internal consistency for the external, internal, and kinesthetic subscales with Cronbach's alphas of .95, .95, and .93 respectively.

North American Adult Reading Test 35

The NAART-35 is a list of 35 irregularly pronounced rare English words. It is used to assess general verbal ability and verbal knowledge (Uttl, 2002). Participants are instructed to read each word aloud and receive a point for each correct pronunciation, leading to a total possible score of 35 on the test. The NAART-35 has demonstrated good reliability, Cronbach's alpha = .92, and good validity, with strong correlations to the full-length NAART ($r = .98$) and Weschler Adult Intelligence Scale - Revised (WAIS-R) vocabulary raw scores ($r = .76$; Uttl, 2002).

Edinburgh Handedness Inventory

The Edinburgh Handedness Inventory is designed to determine overall hand preference (Oldfield, 1970). Participants indicate their preferred hand to use for a variety of daily activities, and the strength of that preference. This is used to calculate a laterality quotient that can range from -100 (left-hand preference, 0 (no preference) to 100 (right-hand preference).

Procedure

Participants were tested individually in the Language Processing Lab. They completed the language processing tasks (the LDT, SCT and SVPT), the HLT, and the MRT on a computer. The TAMI, FPIQ, VMIQ-2, NAART-35 and Edinburgh Handedness Inventory were administered via paper questionnaire. The computer tasks were completed first in the order described above, followed by the questionnaires. Questionnaire order was randomized for each participant. Participants completed the computer tasks and most of the questionnaires independently, although the researcher was present to give face-to-face instructions at the start of each task and was present throughout to answer questions as needed. The NAART was administered face-to-face by the researcher. For each participant, testing lasted approximately 90 - 100 minutes.

Results

Data Cleaning

All data cleaning and analyses were conducted using the statistical software R (Version 3.6.1; R Core Team, 2019). Participants were excluded based on the following criteria: significantly lower than chance performance on the LDT, SCT, SPVT or HLT, below or at chance performance for catch trials on the MRT³ (catch trials defined as trials that had less than 20 degree rotation difference between the two objects), failing to complete the full FPIQ or TAMI, or missing more than one rating on an individual subscale of the VMIQ-2. In addition, one participant was removed from the dataset due to an error in the recording of their LDT and SCT behavioural data. In total, 15 unique participants were excluded from the dataset, leaving 146 participants.

The VMIQ-2 showed high internal consistency, with Cronbach's alphas for the external, internal, and kinesthetic subscales of .94, .91, and .92 respectively. For participants who were missing one rating on at least one subscale of the VMIQ-2, a multiple imputation procedure was used to replace the missing data. Multiple imputation was conducted using the mice package for R (Version 3.8.0; van Buuren & Groothuis-Oudshoorn, 2011), and a mean rating from five different imputation results was used as the replacement value for the missing data points. In total, 11 participants had one missing data point imputed and one participant had two missing data points imputed (each missing data point was on a different subscale) in the dataset. Internal consistency in the VMIQ-2 subscales remained high following imputation, with no changes to the reported Cronbach's alpha values.

³ After our pre-registrations we adjusted the exclusion criteria for the MRT. Our discussions with the developers of the MRT task we used led us to understand that it typically shows lower accuracy than our other tasks. Therefore, we focused on excluding based on poor performance on catch trials. We chose this option to ensure we retained participants who were attending to the task, but did not remove important variability in performance, as this was one of our individual difference measures.

The trial level data for the LDT, SCT, and SPVT were then cleaned. First, any item with significantly lower than chance accuracy was removed from all participants' datasets. This resulted in five words being removed from the LDT, 13 words being removed from the SCT and one sentence/image pair being removed from the SPVT. As a final step of data cleaning, response times that were outliers were excluded for the LDT, SCT, and SPVT. Outliers were any trials with response times that fell ± 3 standard deviations from an individual participant's mean. For full descriptive statistics on accuracies, response times and number of trials included/excluded please see Table 2.

Table 2

Descriptive Statistics for each Language Processing Task

Task	Mean Acc. (%)	SD Acc. (%)	Mean RT (ms)	SD RT (ms)	Trials excluded	Trials included
<i>LDT</i>	95.26	4.29	673.36	231.80	192	13,068
High BOI	94.64	8.08	676.15	239.14	122	6,275
Low BOI	95.74	5.77	670.78	224.80	70	6,793
<i>SCT</i>	90.02	10.82	1116.74	494.36	244	11,357
High BOI	91.63	9.42	1062.75	466.03	99	6,141
Low BOI	87.89	8.62	1180.31	518.65	145	5,216
<i>SPVT</i>	98.57	3.52	833.58	389.52	100	3,261
Congruent	98.60	2.10	827.60	392.16	46	1,634
Incongruent	98.55	2.10	839.59	386.88	54	1,627

Note. $N = 146$. Acc = accuracy; SD = standard deviation; RT = response time on accurate trials; ms = milliseconds; LDT = lexical decision task; SCT = syntactic classification task; SPVT = sentence picture verification task; BOI = body-object interaction.

Exploratory Factor Analysis

As per the planned analyses in our pre-registration, an exploratory factor analysis was conducted to identify latent motor imagery constructs and to extract factor scores for those constructs. The psych package (Version 1.9.12; Revelle, 2019), GPArotation package (Version 2014.11.1; Bernaards & Jennrich, 2005), psycho package (Version 0.4.91; Makowski, 2018), and Hmisc package (Version 4.2.0; Harrell, 2019) were used to conduct the exploratory factor analysis. The following variables were submitted to the exploratory factor analysis for each of the 146 participants: scores on each FPIQ subsection, score on the TAMI, the sum of ratings on each VMIQ-2 subscale, mean response time on the HLT and accuracy on the MRT. Bartlett's test of sphericity was significant, $\chi^2(45) = 165.00$, $p < .001$ and the Kaiser-Meyer-Olkin measure of sampling adequacy was .66, indicating the correlations observed amongst the data are mediocre but adequate for a factor analysis. A scree plot of the observed data and a parallel analysis indicated that it was appropriate to extract a two-factor solution. The solution was extracted using principal axis factoring and an orthogonal rotation was applied to the factor solution. The loadings from the two-factor solution indicated that response time on the HLT did not contribute meaningfully to either factor, so this variable was removed, and the exploratory factor analysis was re-run.

With HLT mean response time removed, Bartlett's test of sphericity was significant, $\chi^2(36) = 157.62$, $p < .001$ and the Kaiser-Meyer-Olkin measure of sampling adequacy was .67, indicating the correlations observed amongst the data were low to adequate for a factor analysis. A scree plot (Figure 1) of the observed data and a parallel analysis indicated that it was still appropriate to extract a two-factor solution. Once again, the factors were extracted using principal axis factoring and an orthogonal rotation was applied to the factor solution due to low correlation between the factors. The structure coefficients and communalities for the items in each factor are presented in Table 3. The first factor accounted for 15.60% of the variance and appears to represent an aspect of motor imagery related to

action and rotation/manipulation of objects, with high loadings from the MRT, the TAMI and the FPIQ subsections related to action and objects. Interestingly, this factor also represented motor imagery abilities that were measured primarily through accuracy and implicit tasks. The second factor accounted for 13.70% of the variance and appears to solely represent self-reported vividness of motor imagery, as it has high loadings exclusively from the VMIQ-2 subscales, with the strongest loading from the VMIQ-2 internal perspective subscale. Factor scores for each participant were extracted for use in subsequent analyses.

Figure 1

Parallel Analysis Scree Plot

Table 3*Exploratory Factor Analysis Factor Loadings for Motor Imagery Variables*

Variable	Action and Rotation	VMIQ	Communality (h2)
FPIQ Action	0.621		0.393
MRT Accuracy	0.537		0.288
TAMI	0.523		0.275
FPIQ Object	0.485		0.245
FPIQ Position	0.343		0.118
VMIQ-2 Internal		0.759	0.578
VMIQ-2 Kinesthetic		0.619	0.384
VMIQ-2 External		0.506	0.264
FPIQ Kinesthetic			0.096

Note. FPIQ = Florida Praxis Imagery Questionnaire; VMIQ-2 = Vividness of Visual Imagery Questionnaire

2. Factor loadings and communalities derived using principal axis factoring with Varimax rotation ($N = 146$). Factor loadings less than 0.32 are not presented here.

Mixed Effect Analyses

The lme4 package (Version 1.1.21; Bates et al., 2015a), lmerTest package (Version 3.1.0; Kuznetsova et al., 2017), the broom.mixed package (Version 0.2.4; Bolker & Robinson, 2019), the performance package (Version 0.6.1; Lüdtke et al., 2020) and the parameters package (Version 0.6.0; Makowski et al., 2019) were used for the mixed effect models. Mean response times, accuracies and standard deviations for the LDT, SCT and SPVT are presented in Table 2. Hypotheses were tested using linear mixed effects models for each task.

All models included fixed effects of motor imagery ability (using the latent motor imagery factors identified in the EFA), gender and NAART score. Gender and NAART were entered to control for potential gender differences and differences in language ability, respectively; however, given that gender was not at all balanced in our sample, gender effects were not interpreted. All correlations between the individual difference variables can be found in Table 4 and distributions of the motor imagery factor scores can be seen in Figure 3. Higher scores on the Action Rotation Imagery factor and lower scores on the Vivid Motor Imagery factor indicate better imagery ability. Handedness laterality quotients (HLQ) from the Edinburgh Handedness Inventory were calculated, however these data were excluded from the models using motor imagery factor scores, as their purpose was to control for handedness differences in performance on the HLT which was not included in the calculation of the factor scores. HLQs are included in follow-up models that report all motor imagery predictors. Task-specific fixed effects are provided in more detail in the following sections for each task. All continuous predictors were standardized before entry into the models and response times were transformed to z-scores.

Table 4*Correlations for Individual Difference Variables*

Variable	FPIQ Kin	FPIQ Pos	FPIQ Act	FPIQ Obj	VMIQ- 2 Ext	VMIQ- 2 Int	VMIQ- 2 Kin	HLT	MRT	HLQ	NAART
TAMI	0.08	0.16	0.33***	0.28***	0.04	-0.01	-0.04	-0.09	0.31***	0.14	0.21*
FPIQ Kin		0.05	0.26**	0.14	0.05	0.09	-0.05	-0.06	0.22**	0.05	0.17*
FPIQ Pos			0.19*	0.24**	0.01	-0.01	0.05	-0.18*	0.21**	0.09	0.18*
FPIQ Act				0.31***	0.08	0.05	0.08	-0.04	0.32***	0.18*	0.21*
FPIQ Obj					0.09	0.14	0.00	0.03	0.20*	0.10	0.22**
VMIQ-2 Ext						0.38***	0.32***	-0.04	0.05	0.04	0.08
VMIQ-2 Int							0.47***	-0.03	0.01	-0.05	-0.06
VMIQ-2 Kin								-0.08	-0.02	-0.07	-0.02
HLT									-0.06	0.04	0.03
MRT										0.00	0.23**
HLQ											0.14

Note. TAMI = Test of Ability in Movement Imagery; ; FPIQ Kin = Florida Praxis Imagery Questionnaire Kinesthetic Subscale ; FPIQ Pos = Florida Praxis Imagery Questionnaire Position Subscale; FPIQ Act = Florida Praxis Imagery Questionnaire Action Subscale; FPIQ Obj = Florida Praxis Imagery Questionnaire Object Subscale; VMIQ-2 Ext = Vividness of Movement Imagery Questionnaire 2 External Subscale; VMIQ-2 Int =

Vividness of Movement Imagery Questionnaire 2 Internal Subscale; VMIQ-2 Kin = Vividness of Movement Imagery Questionnaire 2 Kinesthetic Subscale; HLT = Hand Laterality Task mean response time; MRT = Mental Rotation Task accuracy; HLQ = Handedness laterality quotient; NAART = North American Adult Reading Test. $N = 146$. * $p < .05$, ** $p < .01$, *** $p < .001$.

Figure 2*Distribution of Individual Difference Variables*

Note. TAMI = Test of Ability in Movement Imagery; FPIQ Kin = Florida Praxis Imagery Questionnaire Kinesthetic Subscale ; FPIQ Pos = Florida Praxis Imagery Questionnaire Position Subscale; FPIQ Act = Florida Praxis Imagery Questionnaire Action Subscale; FPIQ Obj = Florida Praxis Imagery Questionnaire Object Subscale; VMIQ-2 Ext = Vividness of Movement Imagery Questionnaire 2 External Subscale; VMIQ-2 Int = Vividness of Movement Imagery Questionnaire 2 Internal Subscale; VMIQ-2 Kin = Vividness of Movement Imagery Questionnaire 2 Kinesthetic Subscale; HLT = Hand Laterality Task mean response time; MRT = Mental Rotation Task accuracy; HLQ = Handedness laterality quotient; NAART = North American Adult Reading Test. $N = 146$.

Figure 3*Distribution of Motor Imagery Factor Scores*

Given that the hypotheses were focused solely on fixed effects, random effects were included only for the purpose of accounting for repeated observations within subjects and items (i.e., word or image) in the study, in order to obtain more powerful tests of the fixed effects (Baayen et al., 2008; Bates et al., 2015b). Random effects that were appropriate for inclusion were selected by starting with a maximal model that specified all possible random intercepts and slopes (Barr et al., 2013) in order to determine how much variance could be accounted for by each random effect. The initial maximal models included random intercepts for subject and item, as well as a random slope of subject. Subsequent models then removed the random slope for subject and were compared to the maximal models using a -2 log likelihood chi square difference test. In the models for the LDT and SPVT, the random slope for subject did not sufficiently contribute to the model to warrant inclusion, and thus only random intercepts for item and subject are included for those models. In the models for the SCT, the

model including a random slope for subject was a significantly better fit than the model which did not include a random slope, and thus these models are reported with the inclusion of the random slope.

We calculated Bayes Factors (*BF*) for each fixed effect using the methods described by Dienes (2014) and an online calculator based on this method (<https://medstats.github.io/bayesfactor.html>).

The alternative hypothesis was modeled as a normal, two-tailed distribution. We extracted the beta and *SE* of each fixed effect in our mixed effect models and calculated *BFs* for a range priors, setting the *SD* of the normal distribution to 0.1, 0.25, 0.5, and 1, with 0.1 representing the smallest anticipated effect size and the basis for our sample size. A *BF* greater than 3 was interpreted as substantial evidence for the alternative hypothesis and less than 0.333 was interpreted as substantial evidence for the null hypothesis. Any *BF* between these two points was considered inconclusive and indicative that the data were too insensitive to test the hypothesis. The entire range of *BFs* are reported in each table, but only the *BF* at the smallest prior of 0.1 *SD* are interpreted in text.

LDT

Only word trials were included in the mixed effects model for the LDT (i.e., nonword trials were excluded). Hypotheses were tested using a linear mixed effects model to predict LDT response time with fixed effects of word type (high BOI noun, low BOI noun), motor imagery ability (using the latent motor imagery factors identified in the EFA) and an interaction between word type and motor imagery. Only one significant fixed effect was identified; NAART scores were significantly related to response time on the LDT, with better performance on the NAART associated with faster response times, $t(140.96) = -3.198$, $p = .002$, $BF_{0.1} = 28.626$. All other fixed effects were not significant, and the *BFs* indicated inconclusive results for all but the interactions. The *BFs* for the word type by action rotation motor imagery and word type by vivid motor imagery interactions indicated substantial evidence for the null hypothesis, $BF_{0.1} = 0.178$ and 0.237 respectively. Refer to Table 5 for estimates of all random and fixed effects, and *BFs*.

Table 5*Linear Mixed Effects Model Predicting LDT Response Time Using Motor Imagery Factor Scores*

Fixed Effects	b	SE	t	p	95% CI		BF			
					LL	UL	BF _{0.1}	BF _{0.25}	BF _{0.5}	BF ₁
Intercept	0.002	0.115	0.015	.988	-0.223	0.227				
Gender	0.005	0.111	0.044	.965	-0.213	0.223	0.743	0.406	0.217	0.110
NAART	-0.127	0.040	-3.198	.002**	-0.204	-0.049	28.626	21.519	11.930	6.125
Word Type	0.041	0.072	0.566	0.573	-0.101	0.182	0.620	0.321	0.167	0.084
Action Rotation	0.028	0.049	0.563	.575	-0.068	0.123	0.502	0.225	0.115	0.058
Vivid Imagery	-0.001	0.045	-0.014	.989	-0.089	0.087	0.410	0.177	0.090	0.045
Word Type* Action Rotation	-0.002	0.018	-0.091	.927	-0.038	0.034	0.178	0.072	0.036	0.018
Word Type* Vivid Imagery	-0.014	0.018	-0.812	.417	-0.049	0.020	0.237	0.097	0.049	0.012
Random Effects	Variance	SD								
Subject intercept	0.189	0.435								
Item intercept	0.118	0.344								
Residual	0.702	0.838								
ICC _{subject and item}	0.304									
Model Fit	Marginal	Conditional								
R ²	0.015	0.315								

Note. LDT = lexical decision task; SD = standard deviation; SE = standard error; CI = confidence interval; LL = lower limit; UL = upper limit; BF =

Bayes Factor; NAART = North American Adult Reading Test; VMIQ = Vividness of Movement Imagery Questionnaire. Model equation: z-score RT

~ Type + Gender + Z_NAART + Action_Rotation + VMIQ + Type*Action_Rotation + Type*VMIQ + (1|Subject) + (1|Item). Word type is a binary variable with high BOI nouns as the focus group and low BOI nouns as the reference group. Gender is a binary variable with female as the focus group and male as the reference group. p -values for fixed effects are calculated using Satterthwaite's method and confidence intervals were calculated using the Wald method. $N = 146$. * $p < .05$, ** $p < .01$, *** $p < .001$.

SCT

Only noun trials were included in the mixed effects model for the SCT, as the task was a go/no-go design and thus no response time data were collected for the no-go trials (i.e., verb trials).

Hypotheses were tested using a mixed effects model to predict SCT response time with fixed effects of word type (high BOI noun, low BOI noun), motor imagery ability, and an interaction between word type and motor imagery ability. The model identified three significant fixed effects. There was a significant effect of word type on response time, $t(89.22) = -3.100$, $p = .003$, $BF_{0.1} = 10.666$, with high BOI nouns responded to more quickly than low BOI nouns. There was also a significant effect of gender, $t(139.46) = -2.788$, $p = .006$, $BF_{0.1} = 5.516$, with females responding significantly faster than males. Finally, there was a significant effect of NAART score, $t(140.20) = -4.265$, $p < .001$, $BF_{0.1} = 933.768$, with higher NAART scores associated with faster response times. All other fixed effects were not significant, and the BFs indicated inconclusive results for all but the word type by vivid motor imagery interaction, which indicated substantial evidence for the null hypothesis, $BF_{0.1} = 0.258$. Refer to Table 6 for estimates of all random and fixed effects, and BFs .

Table 6*Linear Mixed Effects Model Predicting SCT Response Time Using Motor Imagery Factor Scores*

Fixed Effects	b	SE	t	p	95% CI		BF			
					LL	UL	BF _{0.1}	BF _{0.25}	BF _{0.5}	BF ₁
Intercept	0.430	0.107	4.021	<.001***	0.220	0.640				
Gender	-0.256	0.092	-2.788	.006**	-0.435	-0.076	5.516	10.445	7.651	4.247
NAART	-0.139	0.033	-4.265	<.001***	-0.203	-0.075	933.768	800.386	451.216	232.561
Word Type	-0.264	0.085	-3.100	.003**	-0.431	-0.097	10.666	24.278	18.196	10.172
Action Rotation	0.021	0.049	0.415	.679	-0.076	0.117	0.474	0.210	0.107	0.054
Vivid Imagery	0.004	0.046	0.081	.935	-0.087	0.094	0.412	0.178	0.090	0.045
Word Type* Action Rotation	-0.020	0.026	-0.773	.441	-0.072	0.031	0.332	0.139	0.070	0.035
Word Type* Vivid Imagery	-0.009	0.025	-0.346	.730	-0.059	0.041	0.258	0.106	0.053	0.027
Random Effects	Variance	SD	Corr							
Subject intercept	0.197	0.443								
Subject Word Type slope	0.029	0.169	-0.72							
Item intercept	0.148	0.384								
Residual	0.708	0.841								
ICC _{subject and item}	0.299									
Model Fit	Marginal	Conditional								
R ²	0.037	0.325								

Note. SCT = lexical decision task; *SD* = standard deviation; *SE* = standard error; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *BF* = Bayes Factor; NAART = North American Adult Reading Test; VMIQ = Vividness of Movement Imagery Questionnaire. Model equation: z-score RT $\sim$ Type + Gender + Z_NAART + Action_Rotation + VMIQ + Type*Action_Rotation + Type*VMIQ + (1 + Type|Subject) + (1|Item). Word type is a binary variable with high BOI nouns as the focus group and low BOI nouns as the reference group. Gender is a binary variable with female as the focus group and male as the reference group. *p*-values for fixed effects are calculated using Satterthwaite's method and confidence intervals were calculated using the Wald method. *N* = 146. * *p* < .05, ** *p* < .01, *** *p* < .001.

SPVT

Only target trials with the congruency manipulation were included in the mixed effects model for the SPVT. Hypotheses were tested using a mixed effects model to predict SPVT response time with fixed effects of trial type (congruent, incongruent), motor imagery ability, and an interaction between trial type and motor imagery ability. The model identified no significant fixed effects; notably, the effect of trial type was not significant. All other fixed effects were not significant, and the *BFs* indicated inconclusive results. Refer to Table 7 for estimates of all random and fixed effects, and *BFs*.

Table 7*Linear Mixed Effects Model Predicting SPVT Response Time Using Motor Imagery Factor Scores*

Fixed Effects	b	SE	t	p	95% CI		BF			
					LL	UL	BF _{0.1}	BF _{0.25}	BF _{0.5}	BF ₁
Intercept	0.002	0.145	0.014	.989	-0.282	0.287				
Gender	0.025	0.152	0.165	.869	-0.273	0.323	0.839	0.524	0.294	0.152
NAART	-0.036	0.054	-0.659	.511	-0.142	0.070	0.564	0.261	0.134	0.067
Trial Type	-0.029	0.028	-1.051	.293	-0.084	0.025	0.443	0.189	0.095	0.048
Action Rotation	-0.127	0.068	-1.861	.065	-0.260	0.007	1.853	1.331	0.747	0.385
Vivid Imagery	-0.021	0.063	-0.331	.741	-0.144	0.102	0.554	0.257	0.132	0.066
Trial Type*Action Rotation	0.025	0.035	0.713	.476	-0.043	0.093	0.415	0.178	0.090	0.045
Trial Type*Vivid Imagery	-0.021	0.034	-0.610	.542	-0.087	0.046	0.382	0.162	0.082	0.041
Random Effects	Variance	SD								
Subject intercept	0.339	0.582								
Item intercept	0.039	0.198								
Residual	0.632	0.795								
ICC _{subject and item}	0.374									
Model Fit	Marginal	Conditional								
R ²	0.013	0.383								

Note. SPVT = sentence picture verification task; *SD* = standard deviation; *SE* = standard error; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *BF* = Bayes Factor; NAART = North American Adult Reading Test; VMIQ = Vividness of Movement Imagery Questionnaire. Model equation: z-score RT ~ Trial_Type + Gender + Z_NAART + Action_Rotation + VMIQ + Type*Action_Rotation + Type*VMIQ + (1|Subject) +

(1|Item). Trial type is a binary variable with congruent trials as the focus group and incongruent trials as the reference group. Gender is a binary variable with female as the focus group and male as the reference group. p -values for fixed effects are calculated using Satterthwaite's method and confidence intervals were calculated using the Wald method. $N = 146$. * $p < .05$, ** $p < .01$, *** $p < .001$.

Exploratory Analyses

In addition to the analyses pre-registered in our OSF.io project, we ran mixed effect models on language processing task data using the individual motor imagery measures as predictors, rather than the imagery factor scores. These were exploratory analyses conducted subsequent to our pre-registration in order to examine whether more fine-grained measures of motor imagery could account for differences in sensorimotor effects in the language processing tasks. The LDT model with individual motor imagery measures identified no significant relationships, however the models for the SCT and the SPVT identified significant relationships between individual motor imagery measures and response time.

SCT

When using individual motor imagery measures in the model in lieu of motor imagery factor scores, the significant fixed effects remained the same as in the model with the motor imagery factor scores. In addition, a significant interaction emerged between word type and FPIQ Position. There was a significant effect of word type on response time, $t(88.95) = -3.104$, $p = .003$, $BF_{0.1} = 10.666$, with high BOI nouns responded to more quickly than low BOI nouns. There was also a significant effect of gender, $t(130.65) = -3.501$, $p = .001$, $BF_{0.1} = 17.055$, with females responding significantly faster than males. Finally, there was a significant effect of NAART score, $t(131.38) = -4.326$, $p < .001$, $BF_{0.1} = 1323.851$, with higher NAART scores contributing to faster response times. The interaction between word type and FPIQ Position was such that individuals stronger in motor imagery related to hand actions responded more quickly to high BOI words and more slowly to low BOI words, $t(118.75) = -2.697$, $p = .008$, $BF_{0.1} = 6.325$. All other fixed effects were not significant, and the BFs indicated inconclusive results for all but the HLQ ($BF_{0.1} = 0.298$), the word type by FPIQ Kinesthetic subscale interaction ($BF_{0.1} = 0.248$), the word type by FPIQ Action subscale interaction ($BF_{0.1} = 0.240$), and the word type by VMIQ-Kinesthetic subscale interaction ($BF_{0.1} = 0.236$), suggesting substantial evidence for the null hypothesis for these effects. Refer to Table 8 for estimates of all random and fixed effects, and BFs .

Table 8*Linear Mixed Effects Model Predicting SCT Response Time Using Motor Imagery Measures*

Fixed Effects	b	SE	t	p	95% CI		BF			
					LL	UL	BF _{0.1}	BF _{0.25}	BF _{0.5}	BF ₁
Intercept	0.493	0.108	4.560	<.001***	0.281	0.705				
Gender	-0.327	0.094	-3.501	.001**	-0.511	-0.144	17.055	70.578	63.759	37.660
NAART	-0.142	0.033	-4.326	<.001***	-0.206	-0.077	1323.851	1170.883	663.360	342.377
HLQ	0.004	0.031	0.131	.896	-0.057	0.065	0.298	0.124	0.062	0.031
Word Type	-0.264	0.085	-3.104	.003**	-0.431	-0.097	10.666	24.278	18.196	10.172
FPIQ Kin	0.056	0.041	1.369	.173	-0.024	0.136	0.843	0.401	0.206	0.104
FPIQ Position	0.021	0.041	0.512	.610	-0.060	0.102	0.424	0.184	0.093	0.047
FPIQ Action	0.073	0.045	1.640	.103	-0.014	0.161	1.225	0.633	0.331	0.167
FPIQ Object	-0.022	0.043	-0.508	.613	-0.106	0.062	0.441	0.192	0.098	0.049
VMIQ-2 Kin	0.022	0.045	0.489	.625	-0.066	0.111	0.453	0.199	0.101	0.051
VMIQ-2 Int	0.016	0.046	0.354	.724	-0.074	0.107	0.439	0.192	0.097	0.049
VMIQ-2 Ext	-0.058	0.043	-1.355	.178	-0.141	0.026	0.851	0.410	0.211	0.106
TAMI	0.001	0.043	0.012	.990	-0.081	0.085	0.395	0.170	0.086	0.043
MRT	-0.071	0.043	-1.637	.104	-0.155	0.014	1.248	0.637	0.331	0.167
HLT	0.072	0.040	1.804	.074	-0.006	0.149	1.500	0.766	0.399	0.201
Type*FPIQ Kin	-0.012	0.022	-0.547	.585	-0.056	0.031	0.248	0.102	0.051	0.026
Type*FPIQ Position	-0.061	0.023	-2.697	.008**	-0.105	-0.017	6.325	2.995	1.526	0.773
Type*FPIQ Action	-0.006	0.024	-0.259	.796	-0.054	0.041	0.240	0.099	0.049	0.025
Type*FPIQ Object	0.031	0.023	1.327	.187	-0.015	0.077	0.531	0.225	0.114	0.057

Type*VMIQ-2 Kin	-0.004	0.024	-0.178	.859	-0.052	0.044	0.236	0.097	0.049	0.024
Type*VMIQ-2 Int	-0.029	0.025	-1.140	.256	-0.079	0.021	0.457	0.194	0.098	0.049
Type*VMIQ-2 Ext	0.032	0.023	1.356	.178	-0.014	0.077	0.562	0.239	0.121	0.060
Type*TAMI	-0.036	0.024	-1.517	.132	-0.082	0.010	0.676	0.291	0.147	0.074
Type*MRT	0.027	0.023	1.151	.252	-0.019	0.072	0.431	0.181	0.091	0.046
Type*HLT	-0.027	0.021	-1.255	.212	-0.069	0.015	0.453	0.190	0.096	0.048
Random Effects	Variance	SD	Corr							
Subject intercept	0.194	0.440								
Subject Word Type slope	0.027	0.164	-0.74							
Item intercept	0.148	0.384								
Residual	0.708	0.841								
ICC _{subject and item}	0.296									
Model Fit	Marginal	Conditional								
R^2	0.050	0.332								

Note. SCT = syntactic classification task; *SD* = standard deviation; *SE* = standard error; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit;

BF = Bayes Factor; *HLQ* = Handedness laterality quotient; *NAART* = North American Adult Reading Test; *FPIQ* = Florida Praxis Imagery

Questionnaire; *VMIQ-2* = Vividness of Movement Imagery Questionnaire 2; *Kinesthetic* = *KIN*; *Internal* = *Int*; *External* = *Ext*; *TAMI* = Test of Ability

in Movement Imagery; *MRT* = Mental Rotation Task accuracy; *HLT* = Hand Laterality Task mean response time. Model equation: z-score RT ~

Type + Gender + Z_NAART + Z_Hand + Type*Z_FPIQ_A + Type*Z_FPIQ_B + Type*Z_FPIQ_C + Type*FPIQ_D + Type*Z_VMIQ_Kin +

Type*Z_VMIQ_Int + Type*Z_VMIQ_Ext + Type*Z_TAMI + Type*Z_MRT + Type*Z_HLT + (1 + Type|Subject) + (1|Item). Word type is a binary

variable with high BOI nouns as the focus group and low BOI nouns as the reference group. Gender is a binary variable with female as the focus group and male as the reference group. p -values for fixed effects are calculated using Satterthwaite's method and confidence intervals were calculated using the Wald method. $N = 146$. * $p < .05$, ** $p < .01$, *** $p < .001$.

SPVT

When using individual motor imagery measures in the model in lieu of motor imagery factor scores, there emerged a significant effect of HLT, $t(151.73) = 2.043$, $p = .043$, with longer response times on the HLT related to longer response times on the SPVT, however the $BF_{.01} = 2.438$, indicating inconclusive evidence. All other fixed effects were not significant, and the BFs indicated inconclusive results for all but the trial type by FPIQ Kinesthetic subscale interaction ($BF_{0.1} = 0.291$) and the trial type by FPIQ Position subscale interaction ($BF_{0.1} = 0.289$), which suggest substantial evidence for the null hypothesis for these effects. Refer to Table 9 for estimates of all random and fixed effects, and BFs .

Table 9*Linear Mixed Effects Model Predicting SPVT Response Time Using Motor Imagery Measures*

Fixed Effects	b	SE	t	p	95% CI		BF			
					LL	UL	BF _{0.1}	BF _{0.25}	BF _{0.5}	BF ₁
Intercept	0.022	0.150	0.149	.882	-0.271	0.316				
Gender	0.002	0.158	0.011	.991	-0.308	0.311	0.845	0.534	0.301	0.156
NAART	-0.047	0.055	-0.854	.395	-0.155	0.061	0.638	0.304	0.157	0.079
HLQ	0.019	0.053	0.358	.721	-0.084	0.122	0.492	0.220	0.112	0.056
Trial Type	-0.030	0.028	-1.063	.288	-0.084	0.025	0.459	0.196	0.099	0.050
FPIQ Kin	-0.037	0.056	-0.665	.507	-0.147	0.073	0.577	0.269	0.138	0.069
FPIQ Position	-0.037	0.057	-0.660	.511	-0.148	0.074	0.580	0.272	0.139	0.070
FPIQ Action	-0.072	0.061	-1.173	.243	-0.191	0.048	0.865	0.457	0.241	0.122
FPIQ Object	-0.053	0.059	-0.903	.368	-0.168	0.062	0.685	0.337	0.174	0.088
VMIQ-2 Kin	0.017	0.062	0.273	.785	-0.104	0.138	0.541	0.249	0.128	0.064
VMIQ-2 Int	-0.044	0.063	-0.694	.489	-0.168	0.080	0.635	0.307	0.159	0.080
VMIQ-2 Ext	0.046	0.058	0.801	.424	-0.067	0.160	0.635	0.305	0.157	0.079
TAMI	0.008	0.059	0.129	.897	-0.108	0.123	0.511	0.232	0.118	0.059
MRT	0.022	0.059	0.362	.718	-0.095	0.138	0.535	0.245	0.125	0.063
HLT	0.111	0.054	2.043	.043*	0.005	0.217	2.438	1.589	0.866	0.443
Type*FPIQ Kin	0.005	0.030	0.161	.872	-0.054	0.064	0.291	0.121	0.061	0.030
Type*FPIQ Position	0.003	0.030	0.105	.916	-0.056	0.062	0.289	0.120	0.060	0.030
Type*FPIQ Action	0.034	0.033	1.041	.298	-0.030	0.098	0.506	0.220	0.112	0.056
Type*FPIQ Object	-0.025	0.031	-0.789	.430	-0.086	0.037	0.398	0.169	0.089	0.043

Type*VMIQ-2 Kin	-0.031	0.033	-0.939	.348	-0.095	0.033	0.466	0.202	0.102	0.051
Type*VMIQ-2 Int	0.040	0.034	1.176	.240	-0.027	0.106	0.598	0.266	0.135	0.068
Type*VMIQ-2 Ext	-0.044	0.031	-1.433	.152	-0.105	0.016	0.742	0.332	0.169	0.085
Type*TAMI	0.039	0.032	1.240	.215	-0.023	0.102	0.598	0.264	0.134	0.067
Type*MRT	-0.023	0.031	-0.725	.469	-0.084	0.039	0.381	0.161	0.081	0.041
Type*HLT	0.035	0.029	1.215	.225	-0.021	0.091	0.545	0.236	0.120	0.060
Random Effects	Variance	SD								
Subject intercept	0.340	0.582								
Item intercept	0.039	0.198								
Residual	0.632	0.795								
ICC _{subject and item}	0.374									
Model Fit	Marginal	Conditional								
R ²	0.036	0.397								

Note. SPVT = sentence picture verification task; *SD* = standard deviation; *SE* = standard error; *CI* = confidence interval; *LL* = lower limit; *UL* = upper limit; *BF* = Bayes Factor; HLQ = Handedness laterality quotient; NAART = North American Adult Reading Test; FPIQ = Florida Praxis Imagery Questionnaire; VMIQ-2 = Vividness of Movement Imagery Questionnaire 2; Kinesthetic = KIN; Internal = Int; External = Ext; TAMI = Test of Ability in Movement Imagery; MRT = Mental Rotation Task accuracy; HLT = Hand Laterality Task mean response time. Model equation: z-score RT ~ Trial_Type + Gender + Z_NAART + Z_Hand + Trial_Type * Z_FPIQ_A + Trial_Type * Z_FPIQ_B + Trial_Type * Z_FPIQ_C + Trial_Type * FPIQ_D + Trial_Type * Z_VMIQ_Kin + Trial_Type * Z_VMIQ_Int + Trial_Type * Z_VMIQ_Ext + Trial_Type * Z_TAMI + Trial_Type * Z_MRT + Trial_Type * Z_HLT + (1|Subject) + (1|Item). Trial type is a binary variable with congruent trials as the focus group and incongruent trials as the reference group.

Gender is a binary variable with female as the focus group and male as the reference group. p -values for fixed effects are calculated using Satterthwaite's method and confidence intervals were calculated using the Wald method. $N = 146$. * $p < .05$, ** $p < .01$, *** $p < .001$.

Discussion

The purpose of the present research was to investigate the extent to which motor imagery is analogous to the mental simulations that are proposed to contribute to semantic processing. We examined the relationships between individual differences in motor imagery and semantic processing to assess whether stronger motor imagery ability was related to faster processing time overall in lexical-semantic tasks and, more specifically, whether motor imagery ability interacted with previously reported sensorimotor effects in language processing (i.e., BOI effects in LDT and SCT and orientation congruency effect in the SPVT). Such interactions may indicate that individuals with better motor imagery abilities are more sensitive to these manipulations and thus suggest that they are using motor imagery as a means of simulation when completing these tasks.

We identified two latent constructs of motor imagery; one reflecting imagery ability related to action and rotation of objects, and one reflecting vividness of motor imagery. The action-rotation factor scores were comprised of measures from the MRT, FPIQ, and TAMI. The imagery vividness factor scores were comprised solely of self-reported vividness measures collected on the VMIQ-2. The action-rotation imagery factor most closely resembled imagery abilities that would be relevant to semantic dimensions such as BOI, yet our hypothesis that we would observe interactions between motor imagery ability factor scores and sensorimotor manipulations was not supported; there were no significant interaction effects in any of the language processing tasks. Bayes Factors indicated substantial evidence for the null hypothesis for both interaction effects in the LDT and the BOI interaction with vividness of motor imagery factor scores in the SCT. The *BFs* for interactions in the SPVT were inconclusive, suggesting that the data were insensitive for testing this hypothesis. In addition, motor imagery factor scores did not show any significant fixed effects in relation to response times in the LDT, SCT or SPVT. Thus, it would appear that the global motor imagery ability captured by our latent variables shows no relationship to sensorimotor effects in language processing.

We observed a significant relationship between NAART scores and response times; higher NAART scores were negatively associated with response times in the LDT and SCT. This relationship has been observed in previous research on both the LDT (Yap et al., 2012) and the semantic decision task (SDT; Pexman et al., 2017; Pexman & Yap, 2018). The replication of these effects in the present study suggests that participant performance on the language processing tasks is consistent with previous literature; therefore, it seems unlikely that the lack of significant interactions with motor imagery factors should be attributed to issues with the language processing tasks themselves.

Furthermore, there was a significant effect of word type (high vs low BOI) observed in the SCT. Words with higher BOI ratings were processed more quickly, which replicates previous findings of BOI effects in semantic tasks (Hargreaves et al., 2012; Siakaluk et al., 2008; Tousignant & Pexman, 2012; Wellsby et al., 2014). However, we did not replicate previously observed BOI effects in the LDT (Bennett et al., 2011; Pexman et al., 2019), although there are other reports of marginal or null BOI effects in LDT (Hargreaves & Pexman, 2014; Taikh et al., 2015). The likely explanation for the null BOI effect in the LDT is that the LDT requires less extensive semantic processing than that engaged in tasks such as the SCT; indeed, semantic variables typically account for less variance in the LDT and more variance in semantic tasks (Pexman et al., 2019; Yap et al., 2011). Alternatively, the null BOI effects in the LDT could be due to the fact that ~30% of our sample did not have English as their first language. However, current evidence suggests that sensorimotor effects are present but attenuated in second-language processing (Kühne & Gianelli, 2019), therefore we may expect a weaker BOI effect amongst L2 participants, but not necessarily a null effect.⁴

⁴ An examination of our data supports this proposal; when we added first language status as a predictor to our models, we found that there was no effect of English as a first language in the LDT, but an interaction between BOI and English as a first language in the SCT, with BOI effects in SCT attenuated in participants who did

We did not replicate the previously observed congruency effect in the SPVT, despite using closely adapted stimuli and the same procedure as in previous SPVT research (Zwaan & Pecher, 2012)⁵ and the *BFs* indicated inconclusive evidence. Notably, other replication attempts using a manipulation of object orientation in the SPVT have shown small effect sizes and weak support for the alternative hypothesis using Bayes factors (Zwaan & Pecher, 2012). Zwaan and Pecher proposed two reasons as to why this effect might be weak. First, the orientation of the object may not have been integral to the understanding of the sentence as a whole. Rather, object orientation is additional or supplementary information that does not disrupt a participant's fundamental understanding of the sentence's causal structure. Second, the two orientations (horizontal or vertical) do not substantially alter the ability to interact with the object mentioned in the sentence. For example, whether a book is flat on a table or placed vertically on a shelf does not produce major differences in the potential motor affordances of the object. Some proponents of amodal theories may take these findings as evidence that simulation, if invoked at all, is epiphenomenal to language processing; however, given the insensitivity of the data as indicated by the *BFs*, we believe the lack of congruency effect is more consistent with the proposal that recruitment of simulations is context dependent, and can vary by task and situation (Zwaan, 2014).

not have English as a first language, and stronger BOI effects in SCT for participants who reported English as a first language.

⁵ We also conducted a repeated measures ANOVA to replicate the analysis from Zwaan and Pecher (2012). Our ANOVA did not show a significant congruency effect. We then tested whether the lack of congruency effect was influenced by the inclusion of seven new experimental images to replace images missing from the original stimuli using a 2x2 repeated measures ANOVA, with congruency and image (old vs new) as factors. This analysis revealed a significant main effect of image type, with old images responded to significantly faster than the new images we added, but there was no significant main effect of congruency, nor was there a significant interaction between congruency and image.

Our results suggest that general motor imagery ability is not related to BOI effects in language processing. This null relationship may indicate that the mechanisms of sensorimotor simulation engaged in BOI effects are functionally and structurally different from the aspects of motor imagery that were captured by our factor scores. Our exploratory analyses identified an interaction between performance on the FPIQ Position subscale and BOI effects in the SCT. This could indicate that greater specificity is required when assessing a relationship between type of motor imagery and type of sensorimotor effect; certain aspects of motor imagery and certain types of sensorimotor simulation may share some underlying processes, however, further investigation is needed before drawing any conclusions based on this relationship, particularly given that the number of predictors modeled in the exploratory analyses increases the likelihood of identifying false positives.

Limitations and Future Directions

As described in the introduction, the ability to accurately isolate (Madan & Singhal, 2012) and measure individual motor imagery ability (McAvinue & Robertson, 2008) has been one of the foremost challenges to explorations of individual differences in motor imagery to date. To quantify our participants' motor imagery ability, we used a series of different measures, which addressed a variety of underlying dimensions of motor imagery. However, participants' scores on the different measures were only modestly correlated, with the strongest relationships between scores on the FPIQ Action and Object subscales, TAMI, and the MRT. For the VMIQ-2 we only found relationships within its three subscales. Scores on the FPIQ Kinesthetic and Position subscales showed little relationship to most of the other motor imagery measures. This would suggest that, although these instruments are all designed to measure motor imagery, motor imagery is a multidimensional construct.

Furthermore, our factor analysis results differentiated the motor imagery construct in a manner that aligned with how the scores were derived. The action-rotation factor scores were comprised of measures of implicit imagery ability (MRT) and more objectively measured accuracy of motor imagery

(TAMI, FPIQ). The imagery vividness factor scores were comprised solely of self-reported vividness measures collected on the VMIQ-2. This shows a clear dissociation between motor imagery implicit/objective tasks and self-report motor imagery scales that should be accounted for in future research.

Future research investigating the relationship between motor imagery and sensorimotor effects in language processing would benefit from ongoing refinement of the motor imagery construct, as well as the development of additional psychometric tools that are sensitive to individual differences in motor imagery. It is notable that individual differences were detected using the FPIQ in our exploratory analyses, despite this questionnaire typically being used with clinical populations. Thus, we would echo the recommendations of McAvinue and Robertson (2008), that the FPIQ should be validated for use in a non-clinical setting and that more sensitive measures of the dimensions of motor imagery captured in the FPIQ should be developed for use in the general population.

In the present study we used an exploratory factor analysis to cluster aspects of motor imagery that were common amongst the various testing and survey procedures, however by clustering these measures we also may have masked important relationships between subdimensions of motor imagery and sensorimotor effects in language processing. Furthermore, while we believe our sample size was sufficient for our pre-registered analyses, it may not have been sufficient for the exploratory analyses. When combined with the challenges of measuring motor imagery ability, we believe future research will be necessary to systematically explore these relationships further. This may be addressed in future research by testing more fine-grained hypotheses about particular dimensions of motor imagery and their relationships to more specific sensorimotor effects in language processing. For instance, while motor imagery for hand movements may be related to BOI effects, it is possible that the motor imagery indexed by a questionnaire such as the TAMI, which examines whole body movement, may be more related to other examples of sensorimotor effects, such as the embodiment (the degree to which a verb

involves the human body) effects observed in verb processing (Sidhu et al., 2014). In addition, much of the previous research on sensorimotor effects in language processing has focused on verbs (Hauk et al., 2004; Kemmerer et al., 2008; Pulvermüller et al., 2005; Willems et al., 2009). Therefore, future studies may wish to focus on verbs with either high or low motor-related information, as indexed by embodiment ratings.

It is possible that motor imagery and sensorimotor simulations during language processing may share some underlying functional processes, but individual differences in motor imagery ability may not be pronounced enough to meaningfully affect language processing. It may be that a base level of motor imagery ability is all that is needed to support mental simulations during language processing. In this case, one would not expect any relationships with individual differences to emerge. Where this may shift is if we look at those who have high expertise in motor imagery such as athletes or, on the opposite end of the spectrum, those who have extreme deficits in mental imagery. Towards this end, one line of inquiry may be to determine if sensorimotor effects are attenuated for individuals with aphantasia, a condition wherein individuals are unable to create mental images (Zeman et al., 2015). An absence of sensorimotor effects for individuals with aphantasia could suggest that imagery does contribute to sensorimotor simulations during language processing, but that most individuals have sufficient imagery ability to observe sensorimotor effects in language processing.

It may also be beneficial to explore why individuals are more likely to employ sensorimotor simulations during language processing, beyond simply individual differences in ability. For example, differences in the recruitment and use of simulation during language processing may reflect individual preference, rather than ability, for engaging in imagery. If preference for imagery use is a factor, then slower processing of words that are low in sensorimotor information may represent the need to shift from a preferred representational modality to another method in order to access word meaning. To

address this question future research could investigate the relationship between preference for motor imagery use and sensorimotor effects in language processing.

Conclusion

In sum, the results of the present study provide little evidence that individual differences in motor imagery ability are related to sensorimotor effects in language processing. Our exploratory analyses suggest that specific dimensions of motor imagery may be related to specific sensorimotor effects, however further investigations are required to replicate these findings. The replication of the BOI effect in the SCT provides further support for theories of semantic representation that propose word meaning is stored in a flexible, multimodal and multidimensional manner that may include some sensorimotor information. This is incompatible with amodal theories of semantic representation, and rather supports theories of semantic representation which assume at least a partial role of modal simulations in the representation of word meaning and further assume that the recruitment of these simulations are task-dependent. Although further investigations are needed to determine if motor simulations and motor imagery share any underlying processes, the present study has helped advance our understanding of how simulation occurs during language processing. It suggests that indices of general motor imagery ability may not capture processes relevant to specific types of sensorimotor simulation. This insight will help guide the development of more specific hypothesis in future research investigating the nature of sensorimotor simulation in semantic processing.

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