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The Benefits of Sensorimotor Knowledge: Body–Object Interaction Facilitates Semantic Processing

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Abstract

This article examined the effects of body–object interaction (BOI) on semantic processing. BOI measures perceptions of the ease with which a human body can physically interact with a word's referent. In Experiment 1, BOI effects were examined in 2 semantic categorization tasks (SCT) in which participants decided if words are easily imageable. Responses were faster and more accurate for high BOI words (e.g., *mask*) than for low BOI words (e.g., *ship*). In Experiment 2, BOI effects were examined in a semantic lexical decision task (SLDT), which taps both semantic feedback and semantic processing. The BOI effect was larger in the SLDT than in the SCT, suggesting that BOI facilitates both semantic feedback and semantic processing. The findings are consistent with the embodied cognition perspective (e.g., Barsalou's, 1999, Perceptual Symbols Theory), which proposes that sensorimotor interactions with the environment are incorporated in semantic knowledge.

Keywords: Embodied cognition; Sensorimotor knowledge; Semantic Categorization; Semantic processing; Semantic feedback

1. Introduction

Embodied cognition is a growing branch of cognitive science that investigates how interactions between the body and the environment influence the development and structure of the mind (Barsalou, 1999; Clark, 1997; Cowart, 2004; Gibbs, 2006; Lakoff & Johnson, 1999; Pecher & Zwaan, 2005). An important theoretical and empirical issue for embodied cognition researchers is whether abstract cognitive processes and representations are grounded in sensorimotor interactions with the environment. According to Wilson (2002), "[m]ental

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structures that originally evolved for perception or action appear to be co-opted and run ‘off-line,’ decoupled from the physical inputs and outputs that were their original purpose, to assist in thinking and knowing” (p. 633). Wilson provided examples of embodied effects in the cognitive psychology and cognitive linguistics literatures (e.g., mental imagery, memory, reasoning and problem solving, linguistic processing, and concept formation) and suggested that off-line embodied cognition is a pervasive phenomenon in the human mind.

According to the embodied cognition perspective, knowledge acquired through bodily experience is an important aspect of what we know about concepts. For example, in Perceptual Symbols Theory (Barsalou 1999, 2003a, 2003b; Barsalou, Simmons, Barbey, & Wilson, 2003), information is acquired from the environment from many different modalities. These modalities include not only the sensory systems (e.g., vision, taste, smell) but also motor, kinesthetic, and proprioceptive systems (e.g., grasping, manipulating objects, internal feedback from muscles and joints), emotional systems (e.g., fear, excitement), and cognitive systems (e.g., attention, language processing). The knowledge gained through these systems is originally processed in modality-specific memory systems (e.g., visual memory, motor memory) and then becomes increasingly integrated in hierarchical conjunctive or association areas (these areas are similar in spirit to Damasio’s, 1989, convergence zones; see also Edelman & Tononi, 2000). Retrieving conceptual knowledge involves simulation or partial reenactments of the sensorimotor, emotional, and cognitive states implicated at encoding. These ideas have led to the notion that conceptual knowledge is represented in multimodal simulators that, according to Barsalou et al., provide the cognitive representations that support memory, language, and thought. For this study, an important implication is that the conceptual knowledge gained through prior bodily experience would be a source of information accessible to language due to its representation in lexical semantics.

This possibility was explored in a recent study by Siakaluk, Pexman, Aguilera, Owen, and Sears (2008), who examined the effects of sensorimotor knowledge on the recognition of individual words. Siakaluk et al. collected ratings for a variable they called *body–object interaction* (BOI), which measures perceptions of the ease with which a human body can physically interact with each word’s referent. A set of high BOI words (e.g., *mask*) and a set of low BOI words (e.g., *ship*) were then selected; and, more important, these were matched on imageability and concreteness (as well as other lexical and semantic variables). Facilitatory BOI effects were observed in both a lexical decision task (LDT; Is the item an English word?) and a phonological lexical decision task (PLDT; Does the item sound like an English word?)—responses to high BOI words were faster than responses to low BOI words. These BOI effects suggest that sensorimotor information is an integral form of knowledge that is brought to bear even during tasks that involve basic decisions about visually presented words. As such, these results provide support for the embodied cognition perspective and suggest that theories of visual word recognition need to include sensorimotor knowledge as part of lexical semantics.

The results of Siakaluk et al. (2008) can be accounted for by the feedback activation framework of visual word recognition (e.g., Hino & Lupker, 1996; Hino, Lupker, & Pexman, 2002). This framework has been invoked to explain a number of findings in the visual word recognition literature in the last several years, including (a) *facilitatory semantic feedback effects,* such as imageability effects in naming (Strain, Patterson, & Seidenberg, 1995), number of features effects in lexical decision and naming (Pexman, Lupker, & Hino, 2002), polysemy effects in lexical decision and naming (Balota, Ferraro, & Connor, 1991; Hino & Lupker, 1996; Hino et al., 2002), and number of associates effects in lexical decision and naming (Pexman, Hargreaves, Edwards, Henry, & Goodyear, 2007); and (b) *inhibitory semantic feedback effects,* such as synonymy effects in lexical decision and naming (Hino et al., 2002; Pecher, 2001).

The feedback activation framework has several critical assumptions, but our discussion here is focused on those assumptions relevant to the results of Siakaluk et al. (2008) and to the tasks used in this study. First, different kinds of word information are processed in different sets of units: For example, orthographic information is processed by a set of orthographic units, phonological information is processed by a set of phonological units, and semantic information is processed by a set of semantic units. Second, lexical decisions are based on the activation of orthographic units, phonological lexical decisions (and naming responses) are based on the activation of phonological units, and semantic categorization decisions are based on the activation of semantic units (Balota, Paul, & Spieler, 1999; Hino et al., 2002). Third, these different sets of units are interconnected such that processing in one set of units can influence processing in a different set of units (e.g., feedback activation from the semantic units to the orthographic units; Balota et al., 1991; Harm & Seidenberg, 2004). Fourth, whether feedback activation has facilitatory or inhibitory effects on processing will depend on the *nature* of the connections between sets of units (Hino & Lupker, 1996; Pexman, Lupker, & Reggin, 2002). If the connections are many-to-one (i.e., the set of units that sends the activation has many activated representations and the receiving set of units has one activated representation), then facilitatory effects are predicted for processing in the receiving set of units. This is because the activation will help the representation in the receiving set of units to settle relatively rapidly, resulting in faster responding. The final assumption is that words with richer semantic representations will produce faster responses in LDT, PLDT, and naming, due to greater feedback from the semantic units to both the orthographic units and the phonological units.

Regarding the Siakaluk et al. (2008) findings, the feedback activation framework accounts for facilitatory BOI effects in the following manner. High BOI words are presumed to activate more sensorimotor information among semantic representations than low BOI words. As such, for high BOI words there should be stronger feedback activation from semantic representations to both orthographic and phonological representations, resulting in faster settling in these two types of representations and faster response latencies in LDT and PLDT. However, the BOI effects in LDT and PLDT provide only indirect evidence for the idea that words with more sensorimotor information generate greater semantic activation than words with less sensorimotor information because responses in these tasks are based on orthographic and phonological processing and only indirectly on semantic processing. In Experiment 1, we tested for a BOI effect in a task based directly on semantic processing to determine if high BOI words generate more semantic activation than low BOI words.

2. Experiment 1

The expectation that BOI effects should facilitate semantic processing is supported by modeling results reported by Plaut and Shallice (1993). In simulations with their connectionist model, Plaut and Shallice demonstrated that words with richer semantic representations produce faster settling than words with sparser semantic representations; that is, words that initially activate more semantic units also build stronger attractors in semantic space, allowing the system to settle more quickly into a stable pattern of activation, which facilitates responding in tasks involving semantic processing. In this experiment, we examined whether high BOI words, because they activate more sensorimotor information than low BOI words, would also produce faster semantic processing in semantic categorization tasks (SCT). Like other investigators, we assume that responses in SCTs are based on activation of semantic representations (Balota et al., 1999; Hino et al., 2002).

In selecting a decision category for Experiment 1, it was important to choose one that was not confounded with BOI; that is, both high BOI and low BOI words had to be equally typical of the decision category in order that the task be sensitive to semantic processing and not just to decision making. The decision category we chose was "imageable." In Experiment 1A, participants were asked to decide if the items refer to something that is "easily imageable"; in Experiment 1B, participants were asked to decide if the items refer to something that is "not easily imageable"; thus, the same experimental items required either a "yes" response (Experiment 1A) or a "no" response (Experiment 1B). If BOI effects are observed in both Experiments 1A and 1B, the implication would be that the effects are not due to a particular strategy participants employed to deal with yes or no responses. More important, the high BOI and low BOI words were matched on imageability and concreteness. If high BOI words have richer semantic representations than low BOI words (and thereby activate more sensorimotor information when read), then facilitatory BOI effects should be observed, assuming that richer semantic representations generate greater semantic activation and faster settling times (Plaut & Shallice, 1993).

2.1. Method

2.1.1. Participants

Two groups of 35 undergraduate students from the University of Northern British Columbia participated in the experiments for bonus course credit. All were native English speakers and reported normal or corrected-to-normal vision.

2.1.2. Stimuli

The words were chosen using the BOI ratings collected by Siakaluk et al. (2008). In that study, participants rated each word according to the ease or difficulty with which a human body can physically interact with each word's referent, using a scale ranging from 1 (*low body–object interaction*) to 7 (*high body–object interaction*). Using these ratings, 24 high BOI words (e.g., *mask*) and 24 low BOI words (e.g., *ship*) were selected (hereafter referred to as the experimental items). The high BOI and low BOI words were matched for length; printed frequency (from the CELEX database; Baayen, Piepenbrock, & Gulikers, 1995); subjective familiarity (Balota, Pilotti, & Cortese, 2001); orthographic and phonological neighborhood sizes (http://www.maccs.mq.edu.au/∼colin/Bristol/N-Watch.zip); phonological feedback inconsistency (http://www.rhymezone.com); number of features (see Siakaluk et al., 2008); number of senses (ITP Nelson, 1997); number of associates (Nelson, McEvoy, & Schreiber, 1998);

semantic distance[1] (see Buchanan, Westbury, & Burgess, 2001); contextual dispersion (Zeno, Ivens, Millard, & Duvvuri, 1995); and, more important, imageability (Cortese & Fugett, 2004) and concreteness (concreteness ratings for 42 of the stimuli were taken from the MRC psycholinguistic database, Coltheart, 1981; and ratings for the remaining 6 stimuli were collected from 25 participants using the Toglia & Battig, 1978, instructions; all ps $> .15$). The descriptive statistics for the experimental items are presented in Table 1; the stimuli are listed in the Appendix.

Forty-eight less imageable nouns were used as filler items. These words had a mean imageability rating of 2.6 (range of 1.8–3.2; Cortese & Fugett, 2004). They were matched to the experimental items on length and had similar normative frequencies ($M = 18.9$).

2.1.3. Apparatus and procedure

The stimuli were presented on a color VGA monitor driven by a pentium-class microcomputer running DirectRT software (http://www.empirisoft.com/DirectRT.aspx). A trial was initiated by a fixation marker that appeared at the center of the computer display. The fixation marker was presented for 1,000 msec and was then replaced by a word. The participants' task was to read the word and then make a speeded semantic decision. In Experiment 1A, the decision was, "Does the word refer to something that is easily imageable?"; "yes" responses were made by pressing the "?" key on the keyboard, and "no" responses were made by pressing the "z" key. In Experiment 1B, the decision was, "Does the word refer to something that is not easily imageable?"; "yes" responses were made by pressing the "z" key, and "no" responses were made by pressing the "?" key. Thus, in Experiment 1A the experimental items required a "yes" response, whereas in Experiment 1B the same items required a no response. Participants were asked to make their responses as quickly and as accurately as possible. Response latencies were measured to the nearest millisecond. The order in which the stimuli were presented was separately randomized for each participant. The intertrial interval was 2,000 msec.

Each participant first completed 20 practice trials, consisting of 10 imageable words and 10 less imageable words. All practice stimuli were similar in normative frequency to the experimental items.

2.2. Results

Response latencies faster than 250 msec or slower than 2,500 msec were treated as outliers and removed from the data sets. In addition, for each participant, response latencies greater than 2.5 standard deviations from the cell mean of each condition were treated as outliers and removed from the data sets. A total of 49 observations (2.9% of the data) and 47 observations (2.8% of the data) were removed from the data sets of Experiment 1A and Experiment 1B, respectively. In the subject analysis (t_1), BOI was a within-subjects manipulation; in the item analysis (t_2), BOI was a between-item manipulation. Unless noted, all effects were significant at $p < .05$. The mean response latencies for correct responses and mean error percentages are presented in Table 2.

Table 1
Mean characteristics for word stimuli

Word type	BOI	Freq	SubF	N	PN	PFI	NumF	NumS	NumA	SemD	CD	Image	Conc
High BOI	5.3	17.3	3.5	7.1	14.7	3.0	3.4	5.7	14.3	307.7	.69	6.3	5.9
Low BOI	3.3	17.3	3.6	6.4	13.1	3.0	3.7	4.8	13.3	307.8	.68	6.2	5.8

Note. BOI = body–object interaction; Freq = print frequency; SubF = subjective familiarity; N = orthographic neighborhood size; PN = phonological neighborhood size; PFI = phonological feedback inconsistency; NumF = number of features; NumS = number of senses; NumA = number of associates; SemD = semantic distance; CD = contextual dispersion; Image = imageability; Conc = concreteness.

Table 2
Mean response latencies (in milliseconds) and standard errors, and mean error percentages and standard errors

	SCT–1A		SCT–1B		SLDT	
Word type	*M*	SE	*M*	SE	*M*	SE
Response latencies						
High BOI	662	19.0	687	18.7	797	17.6
Low BOI	703	19.2	740	21.4	886	23.8
BOI effect	+41		+ 53		+89	
Less imageable words	867	29.2	884	28.1	—	—
Pseudohomophones	—	—	—	—	988	24.9
Response errors						
High BOI	1.9	0.5	1.8	0.6	1.8	0.6
Low BOI	5.0	0.9	7.3	1.4	5.9	1.5
BOI effect	+3.1		+5.5		+4.1	
Less imageable words	12.3	1.5	11.0	1.9	22.9	2.1
Pseudohomophones	—	—	—	—	3.3	0.7

Note. SCT = semantic categorization task; SLDT = semantic lexical decision task; BOI = body–object interaction.

2.2.1. Experiment 1A

There was an effect of BOI in the analysis of the response latency data—$t_1(34) = 4.61$, $SE = 8.87$, $\eta^2 = .38$; $t_2(46) = 2.56$, $SE = 17.75$, $\eta^2 = .12$—and in the analysis of the response error data—$t_1(34) = 4.44$, $SE = .90$, $\eta^2 = .37$; $t_2(46) = 2.17$, $SE = 1.81$, $\eta^2 = .09$. Responses to high BOI words were faster and more accurate than responses to low BOI words.

2.2.2. Experiment 1B

There was an effect of BOI in the analysis of the response latency data—$t_1(34) = 4.53$, $SE = 11.80$, $\eta^2 = .38$; $t_2(46) = 3.06$, $SE = 19.98$, $\eta^2 = .17$—and in the analysis of the response error data—$t_1(34) = 5.31$, $SE = 1.03$, $\eta^2 = .45$; $t_2(46) = 2.73$, $SE = 2.04$, $\eta^2 = .14$. As in Experiment 1A, responses to high BOI words were faster and more accurate than responses to low BOI words.

2.3. Discussion

We observed facilitatory BOI effects in two tasks in which responses are based on the activation of semantic representations. This occurred in experimental contexts in which the same items required either a "yes" response (Experiment 1A) or a "no" response (Experiment 1B). As such, the effects are unlikely to be due to particular strategies participants applied to make positive or negative decisions. These findings are consistent with the previous findings of facilitatory BOI effects in LDT and PLDT (Siakaluk et al., 2008). This study advances this previous research by providing more direct evidence that semantic processing is facilitated for words with more sensorimotor information, as the data are from tasks that depend more heavily on accessing semantics. It seems likely that this facilitation occurs because representations for high BOI words incorporate more sensorimotor information (e.g., stored motor program, affordance, proprioceptive, and kinesthetic information) than do representations for low BOI words.

3. Experiment 2

A second purpose of this study was to discern the source of facilitatory BOI effects; that is, thus far we have described two possibilities: In Experiment 1, the facilitatory BOI effects were attributed to semantic activation and processing within the semantic representations themselves. On the other hand, the facilitatory BOI effects in LDT and PLDT (Siakaluk et al., 2008) were attributed to feedback activation from semantic representations to orthographic representations (in the LDT) or to phonological representations (in the PLDT). In Experiment 2, we examined the effects of BOI in a task that should be sensitive to both of these mechanisms: semantic processing and semantic feedback activation.

The task in this experiment required two decisions. First, participants had to decide if an item was a word or not ("yes" or "no"; some of the items were nonwords); second, if the item was a word, participants had to decide if it was easily imageable. We refer to this as a semantic lexical decision task (SLDT), and made the following assumptions about this task. First, because participants must decide if the item is a word or nonword, responses will be based partly on the activation of orthographic representations, and the decision should be sensitive to effects of semantic feedback activation. Second, because participants must also make a semantic decision ("Is it easily imageable?"), responses will be based partly on the activation of semantic representations, and the decision should be sensitive to effects of activation within those semantic representations. Thus, with the SLDT, both the semantic feedback and semantic processing mechanisms will be involved in the response process.

3.1. Method

3.1.1. Participants

Thirty-five undergraduate students from the University of Northern British Columbia participated in the experiment for bonus course credit. None of these students participated in Experiment 1. All participants were native English speakers and reported normal or corrected-to-normal vision.

3.1.2. Stimuli

The word stimuli consisted of the same items used in Experiment 1. We used pseudohomophones as nonword fillers to encourage extensive orthographic processing (Pexman & Lupker, 1999; Stone & Van Orden, 1993). The set of 48 pseudohomophones were also used by Siakaluk et al. (2008). The pseudohomophones all had extant word bodies (Vanhoy & Van Orden, 2001) and were matched to the experimental items on length. (The pseudohomophones are listed in the Appendix.)

3.1.3. Apparatus and procedure

The apparatus was the same as in Experiment 1. Participants were asked to decide whether each item was a word or a nonword, and if the item was a word to then decide if the word was easily imageable or not. If the item was a word that was easily imageable (i.e., an experimental item), participants pressed the "?" key; and if the item was a word that was not easily imageable, participants did not press a key. If the item was a pseudohomophone, participants pressed the "z" key. Although these instructions may seem complex, the fact that error rates were quite low (see Table 2) indicates that the task was not particularly difficult. Participants were asked to respond as quickly and as accurately as possible. If no key press was made within 2.5 sec, the item was erased from the display and the next item was presented.

Each participant first completed 24 practice trials, consisting of 8 imageable words, 8 less imageable words, and 8 pseudohomophones. The practice words were similar in normative frequency to the experimental items.

3.2. Results

For each participant, response latencies greater than 2.5 standard deviations from the cell mean of each condition were treated as outliers and removed from the data set. A total of 54 observations (3.2% of the data) were removed by this procedure. Two analyses were conducted. First, to examine the BOI effect in the SLDT, BOI was a within-subjects manipulation in the subject analysis (t_1) and a between-item manipulation in the item analysis (t_2). Second, to determine if the BOI effect was larger in the SLDT than in the SCT of Experiment 1A, a combined analysis of the data from Experiments 1A and 2 was carried out to test for an interaction between BOI and type of task (SCT vs. SLDT). Type of task was a between-subject manipulation in the subject analysis (F_1) and a within-item manipulation in the item analysis (F_2).

3.2.1. SLDT

The mean response latencies of correct responses and mean error percentages for all stimuli are presented in Table 2. The effect of BOI was significant in the analysis of the response latency data—$t_1(34) = 6.68$, $SE = 13.34$, $\eta^2 = .57$; $t_2(46) = 3.58$, $SE = 26.97$, $\eta^2 = .22$—and in the analysis of the response error data—$t_1(34) = 3.03$, $SE = 1.26$, $\eta^2 = .24$; $t_2(46) = 2.47$, $SE = 1.84$, $\eta^2 = .12$. As was the case in Experiment 1, responses to high BOI words were both faster and more accurate than responses to low BOI words.

3.2.2. SLDT versus SCT

The BOI effect on the response latency data was significantly larger in the SLDT (89 msec) than in the SCT (41 msec), $F_1(1, 68) = 9.08$, $MSE = 2{,}245.44$, $\eta^2 = .12$; $F_2(1, 46) = 9.60$, $MSE = 1{,}646.42$, $\eta^2 = .17$. For the response error data, there was no difference in the BOI effect between the two tasks, both Fs < 1 (4.15% & 3.98% for the SLDT and the SCT, respectively).

3.3. Discussion

In this experiment, we used the SLDT to test for the effects of BOI and to determine the source of these effects. This task requires two decisions: a "word" decision that should be sensitive to effects of feedback activation from semantics to orthography and an "imageability" decision that should be sensitive to effects of semantic processing. The effects of BOI in this task were facilitatory, with responses to high BOI words faster and more accurate than responses to low BOI words. The fact that the facilitatory effects of BOI were significantly larger in the SLDT (89 msec) than in the SCT of Experiment 1A (41 msec) suggests that the effects of BOI on semantic feedback and semantic processing are additive. Consistent with this possibility, the 89-msec BOI effect in this experiment is not significantly different from the sum of the BOI effects reported in the SCT (41 msec) of Experiment 1A and the LDT (35 msec) in Siakaluk et al. (2008), one-sample $t(34) < 1$.[2]

4. General discussion

The purpose of this study was to test the idea that words with more sensorimotor information (high BOI words) generate greater semantic activation than words with less sensorimotor information (low BOI words). We observed facilitatory BOI effects—faster and more accurate responses to high BOI words than to low BOI words—in three tasks requiring semantic decisions. We also observed significantly larger BOI effects in the SLDT of Experiment 2 in which responses are assumed to be based on the activation of semantic representations *and* orthographic representations. These findings support the conclusion that BOI effects arise because this variable facilitates semantic processing. Because high BOI words and low BOI words were matched in all other respects, it seems likely that it is the additional knowledge regarding BOIs for high BOI words that created richer semantic representations and facilitated semantic processing. As such, our results imply that any account of lexical semantics needs to incorporate sensorimotor knowledge as an integral component of what humans know about concepts.

The results of this study can be accounted for by the feedback activation framework of visual word recognition described earlier (Hino & Lupker, 1996; Hino et al., 2002). Further, in tasks in which a semantic categorization decision is made, words with richer semantic representations will produce faster semantic categorization responses. This assumption is supported with evidence from both simulations and neuroimaging. As noted, according to Plaut and Shallice's (1993) simulations with their connectionist model, these words build stronger attractors in semantic space. Note that this assumption can also be made consistent with activation-based models like the interactive-activation model (McClelland & Rumelhart, 1981). In these types of models, facilitation of semantic categorization responses may occur because responses may be sensitive to the degree of activation in the set of semantic units, with words generating greater semantic activation (e.g., high BOI words) eliciting faster responses. Recently, Pexman et al. (2007) reported a related finding in a study examining SCT response latency and event-related functional magnetic resonance imaging data. They observed that words with richer semantic representations (i.e., words with many associates) were responded to more quickly and produced lower levels of neural activation in a number of brain regions associated with semantic processing than words with less rich semantic representations (i.e., words with few associates). They proposed that the decrease in neural activation associated with words with richer semantic representations could be attributed to more efficient processing for these words because they have better organized attractors in semantic space (see also Wheatley, Weisberg, Beauchamp, & Martin, 2005).

The findings of this study could be accounted for in the following manner. In the SCTs of Experiment 1, high BOI words activate more sensorimotor information than low BOI words, leading to faster semantic categorization responses. This outcome can be due to either faster settling of semantic representations (as in Plaut & Shallice's, 1993, connectionist model) or the lexical system being sensitive to degree of activation in the set of semantic units (as in McClelland & Rumelhart's [1981] interactive-activation model), with faster settling or greater activation enabling faster responses. In either case, high BOI words would be responded to faster than low BOI words. The same semantic processing mechanism would be at work in the SLDT of Experiment 2. In addition, however, feedback activation from semantics to orthography would also be involved because of the lexical decision component of the task. Because high BOI words would generate more semantic feedback activation than low BOI words, they would receive more facilitation from this mechanism as well.

We have argued that our results are consistent with the notion that sensorimotor information is incorporated in lexical semantics. This is not the only possible explanation of our results, and we next consider two alternative explanations.[3] A first possibility is that the decision category used in the SCT prompted participants to emphasize sensorimotor information for the words presented. Both sets of BOI words were matched on imageability, but the decision category in the SCT made the words' sensorimotor information highly salient; and, as a result, participants may have emphasized information gained through the *motor* modality such as stored motor program, affordance, and proprioceptive and kinesthetic information. The nature of this motor information is discussed in more detail later. The point here is that our results may be a function of the particular experimental context (i.e., making imageability decisions). In this context, modality-specific motor information is accessed, and words that activate more of this type of information lead to faster semantic categorization responses. Further experimentation is necessary to determine if this embodiment effect generalizes to SCTs with different decision criteria.

A second possibility is that activated motor information for high BOI words primes the associated actions in motor cortex, and it is possible that these associated actions are primarily manual in nature. As a result of this type of motor priming, button presses are faster to high BOI words than to low BOI words. One way to test this explanation would be to conduct an experiment in which participants do not make a motor response like that required for a button press, which may be especially sensitive to manual motor actions. For example, a task requiring a verbal response would be less sensitive to manual motor priming, although verbalizations are of course motor responses. The key point here is that motor programs for verbalization are less likely to be used when people physically interact with objects. If BOI effects are still observed when participants make lexical or semantic judgments in tasks requiring verbal responses, then this explanation would not be supported.

A critical issue for our research is what kinds of sensorimotor information could BOI ratings be capturing? One possibility is proprioceptive or kinesthetic information such as the information the brain receives from muscle, joint, and skin receptors regarding the movement and positioning of the body and its parts during interactions with objects in the environment (Gibbs, 2006). Another possibility is stored motor program information, such as the typical motor operations the body uses for physically interacting with a particular object. Yet another possibility is affordance information. Affordances are the possible actions an agent can make in relation to an object (Gibbs, 2006; Gibson, 1979; Glenberg & Robertson, 2000). Consider our examples: *Mask* is a high BOI word, and *ship* is a low BOI word. Masks are objects that human bodies can easily interact with. Much proprioceptive and kinesthetic information is likely made available through the act of picking up, putting on, and taking off masks; and these actions also likely require fairly routinized motor programs. Masks also offer relatively clear affordances, or ways in which human bodies can interact with them. In contrast, ships are objects that human bodies cannot easily interact with; and they offer little, if any, proprioceptive and kinesthetic information and presumably no affordances. It is possible that any or all of these types of information are brought to bear when understanding the meanings of words; therefore, additional research will be necessary to specify the types of sensorimotor information BOI ratings are capturing.

All of these explanations of how sensorimotor information may influence responding in SCTs are consistent with embodied views of cognition, such as that proposed by Barsalou and colleagues (Barsalou, 1999, 2003a, 2003b; Barsalou et al., 2003; see also Paivio, 2007). According to Barsalou's (1999) Perceptual Symbols Theory, sensorimotor experience is vital in developing conceptual knowledge; conceptual knowledge is multimodal in that it is acquired, and represented, through different sensorimotor, emotional, and cognitive modalities. Likewise, retrieval of semantic knowledge involves simulation or partial neural reenactment of those states (whether sensorimotor, emotional, or cognitive) that were present when the conceptual knowledge was first acquired. According to this view, semantic knowledge is represented in terms of multimodal simulators—when a concept is accessed, some subset of the multimodal knowledge is activated, and a mental simulation involves reenacting some aspects of that concept. Our results are consistent with the notion that people use knowledge about bodily interaction with objects to make semantic decisions—in particular, semantic decisions to visually presented words.

5. Conclusion

In this work, we show that BOI, a variable measuring sensorimotor knowledge, influences semantic processing. These findings support the conclusion that words with more sensorimotor knowledge generate greater semantic activation than words with less sensorimotor knowledge, and that this greater semantic activation leads to more efficient semantic processing. These findings also demonstrate the need for theories of visual word recognition to incorporate sensorimotor knowledge as an essential form of knowledge contained in lexical semantics.

Notes

1. We thank Chris Westbury for making these values available to us.
2. Of course, these statistics are based on between-subject comparisons and so should be interpreted with caution.
3. We thank two anonymous reviewers for suggesting these explanations.

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Appendix: Items used in the experiments

High body–object interaction (BOI) words

belt brick couch crown crumb dish drum fence flute gift grape lamp mask pear pipe purse rope skirt stool suit tape thorn tool vest

Low BOI words

cake cliff cloud clown creek dirt ditch dorm flame flood juice kite lace leaf mist pond seed shelf ship silk smog torch tribe tube

Less imageable words

chasm clout cusp farce fare fate fault feat flaw fleck fluke fraud froth gist hint hoax lack lapse loss luck noun oath pact pang phase plea ploy pride proof prose realm risk sake scorn sect skill soul span spoof tact trait trend truce trust verb whiff whim zeal

Pseudohomophones

berd boal boan bote brane crain dait doar drane gaim gard goast gote groop gurl hoam hoap hoze jale jerm jirk joak klaim koast nale noat nurve rane rong rore roze scail sheat shurt skalp skarf sleap smoak stawl stoar swet teath thret tode treet tutch werk wheet