Getting a Grip on Sensorimotor Effects in Lexical-Semantic Processing

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Abstract

One of the strategies that researchers have used to investigate the role of sensorimotor information in lexical-semantic processing is to examine effects of words' rated body-object interaction (BOI; the ease with which the human body can interact with a word's referent). Processing tends to be facilitated for words with high BOI compared to words with low BOI, across a wide variety of tasks. Such effects have been referenced in debates over the nature of semantic representations, but their theoretical import has been limited by the fact that BOI is a fairly coarse measure of sensorimotor experience with words' referents. In the present study we collected ratings for 621 words on seven semantic dimensions (graspability, ease of pantomime, number of actions, animacy, size, danger, and usefulness) in order to investigate which attributes are most strongly related to BOI ratings, and to lexical-semantic processing. BOI ratings were obtained from previous norming studies (Bennett, Burnett, Siakaluk, & Pexman, 2011; Tillotson, Siakaluk, & Pexman, 2008) and measures of lexical-semantic processing were obtained from previous behavioural megastudies involving the semantic categorization task (concrete/abstract decision; Pexman, Heard, Lloyd, & Yap, 2017) and the lexical decision task (Balota et al., 2007). Results showed that the motor dimension of graspability, ease of pantomime, and number of actions were all related to BOI and that these dimensions together explained more variance in semantic processing than did BOI ratings alone. These ratings will be useful for researchers who wish to study how different kinds of bodily interactions influence lexical-semantic processing and cognition.

Getting a Grip on Sensorimotor Effects in Lexical-Semantic Processing

In recent years, studying sensorimotor effects in lexical-semantic processing has been a vibrant topic of research. This interest has been driven largely by the relevance of these effects to theories of semantic representation. In particular, embodied semantic theories claim that retrieval of word meaning, even in simple reading and semantic decision tasks, involves activation of the sensorimotor and perceptual systems (e.g., Barsalou, 2008; Glenberg, 2015). As such, sensorimotor effects in lexical-semantic processing have been used to test the viability of embodied accounts of semantic representation.

One common strategy researchers have used to study sensorimotor effects in lexical processing is to examine effects of words' rated body-object interaction (BOI). BOI has been a focus of study because the dimension captures the relative availability of sensorimotor information (Hargreaves, Leonard, Pexman, Pittman, Siakaluk, & Goodyear, 2012). Ratings of BOI are intended to measure the ease with which the human body can interact with a word's referent (Siakaluk, Pexman, Aguilera, Owen, & Sears, 2008). Words whose referents afford relatively more BOI (e.g., *toothbrush*) are typically processed faster than words whose referents afford fewer opportunities for interaction (e.g., *elephant*) (Siakaluk et al., 2008a; Siakaluk, Pexman, Sears, Wilson, Locheed, & Owen, 2008). Facilitation for high BOI words in lexical-semantic tasks is typically attributed to richer semantic representations of motoric interactions for those items (Pexman, 2012; Yap, Pexman, Wellsby, Hargreaves, & Huff, 2012).

The facilitation of lexical-semantic processing for words with high BOI ratings vs. words with low BOI ratings (hereafter the "BOI effect") is now well established, having been replicated and demonstrated across a variety of contexts. For example, the BOI effect has been observed in lexical decision tasks (LDT) (Siakaluk et al., 2008a; Tillotson, Siakaluk, & Pexman, 2008; Van Havermaet & Wurm, 2014), semantic decision tasks (e.g., “Is it concrete?”, “Is it easily imageable?”)(Bennett, Burnett, Siakaluk, & Pexman, 2011; Hansen, Siakaluk, & Pexman, 2012; Hargreaves et al., 2012; Siakaluk et al., 2008b; Tousignant & Pexman, 2012; Yap et al., 2012), a semantic lexical decision task (i.e., “is it a word?” then “Is it easily imageable?”, Siakaluk et al., 2008b), sentence reading (Phillips, Sears, & Pexman, 2012), and with child participants in auditory word naming (6 – 7-year-old children; Inkster, Wellsby, Lloyd, & Pexman, 2016) and in printed word naming (8 – 9-year-old children; Wellsby & Pexman, 2014). The BOI effect has also been observed using fMRI: high BOI words were associated with higher levels of activation in the left inferior parietal lobule (a sensory association area involved in the planning of object-directed hand movements; van Elk, 2014) than were low BOI words (Hargreaves et al., 2012). The fact that BOI effects are observed in lexical-semantic tasks suggests that children and adults routinely access information about their past sensorimotor experience with words’ referents when making decisions about word meaning. Thus, BOI effects have been taken as evidence that sensorimotor information is important to representations of word meaning, although they cannot adjudicate between models that assume sensorimotor information is necessary for meaning activation (e.g., Glenberg, 2015) and those that assume sensorimotor information is simply activated as a by-product of meaning activation (e.g., Mahon, 2015).

The BOI effect has been frequently observed, but the precise nature of the information captured by the BOI dimension is not well specified. That is, BOI is a rather coarse semantic dimension that seemingly captures a variety of types of sensorimotor information and does not specify the nature of the interaction. Of particular relevance to the present study is the fact that the contribution of specific kinds of *motor* experience to facilitatory BOI effects has not previously been examined. The imprecision of the BOI measure makes it challenging to draw theoretical conclusions, because it is not clear what aspects of bodily information are being activated when word meanings are retrieved. The goal of the present study was to identify which aspects of motor experience drive BOI effects in order to better understand the BOI effects observed thus far, and to help refine theories of semantic representation by specifying the types of motor information involved in lexical-semantic processing.

Candidate Motor Dimensions

There are several more specific motor dimensions that may drive the BOI effects observed in lexical-semantic processing. In particular, there are specific aspects of object manipulation that have primarily been explored in the cognitive neuroscience, neuropsychology, and/or object recognition literatures, where the stimuli are line drawings or photographs (e.g., Boronat et al., 2005; Garcea & Mahon, 2012; Guérard, Lagacé & Brodeur, 2015; Madan, Chen, & Singhal, 2016; Madan, Ng, & Singhal, 2018; Salmon, McMullen & Filliter, 2010; Salmon, Matheson, & McMullen, 2014; Tobia & Madan, 2017). In the present work we considered whether these specific dimensions are related to BOI and whether they also explain word recognition behavior. We chose three candidate motor dimensions that have been shown in the object recognition literature to be related but also somewhat distinct aspects of objects' motor attributes (Guérard et al., 2015).

Graspability. Graspability ratings provide a measure of how easily a person can grasp an object with one hand (Salmon et al., 2010). Many of the words that are rated as high BOI refer to objects that seem easily graspable (e.g., *scissors*). Thus, it is plausible that the facilitation effect observed for high BOI words in lexical-semantic tasks is actually driven by sensorimotor information captured by graspability. Whereas graspability is based on how easily the *hand* can interact with a word's referent, BOI measures the ease with which *any part* of the body can interact with the word's referent. Nonetheless, the fact that the hands are primary for most human interactions with objects means that there is likely a good deal of overlap in the two dimensions. Effects of graspability have been investigated in both object recognition (Grèzes & Decety, 2002; Guérard, et al., 2015; Salmon et al., 2014) and word recognition (Amsel, Urbach, & Kutas, 2012; Díez-Álamo, Díez, Alonso, Vargas, & Fernandez, 2017) research. Two previous studies examined the relationship between graspability and BOI for word stimuli: Amsel et al. (2012) found a moderate correlation of $r = .62$ between the two dimensions for a set of 266 words, Díez-Álamo et al. (2017) found $r = .75$ for the same relationship in a set of 342 Spanish words. Thus, there is evidence suggesting that there is indeed overlap in the types of motoric information captured by these two measures, but neither previous study explored their relative contributions to lexical processes.

Ease of pantomime. Ease of pantomime refers to how easily one can pantomime an object's functional use so that another individual could guess the identity of the object (Brodeur Dionne-Dostie, Montreuil, & Lepage, 2010; Guérard, et al. 2015; Magnié et al., 2003). For example, the referent for *wharf* would be difficult to pantomime whereas *doorknob* would be easy (e.g., making a cupping shape with your hand and twisting at the wrist). This dimension depends on functional actions and so it likely taps how readily one can retrieve the conceptual knowledge associated with the object. Indeed, ease of pantomime is related to object naming latencies, with faster latencies for objects that are easier to pantomime (Guérard, et al. 2015). As BOI captures the ease with which the human body can interact with a word's referent, which typically occurs through functional use of the referent, it is plausible that ease of pantomime may be related to BOI for word stimuli and may drive or help drive the BOI effect.

Number of actions. The number of actions dimension captures the number of functional actions that can typically be performed with an object (Guérard et al. 2015; Lagacé, Downing-Doucet, & Guérard, 2013). This dimension also has a relationship with object naming latencies, such that objects that afford more actions are associated with faster object naming (Guérard et al. 2015). Interaction between a word's referent and the human body typically occurs while using the referent for a functional purpose. For example, a word with a referent that affords few actions (e.g., *fleck*) is unlikely to be easy for the human body to interact with, while a word with a referent that affords many actions (e.g., *baby*, holding, cuddling, playing, etc.) is very easy for the human body to interact with. Thus, high BOI words may afford relatively more actions and motor information regarding the number of actions a word's referent affords may drive or help drive the BOI effect.

Other Non-Motor Dimensions Related to BOI

Several other semantic dimensions might be related to BOI. In particular, we expected that animacy, size, danger, and usefulness might be relevant. BOI attempts to capture the ease with which the human body can interact with a word's referent and so it is possible that words with referents that are small, inanimate, nondangerous, and useful would be rated high on this dimension and that these factors may be related to the facilitation effect observed for BOI in lexical-semantic processing. Previous research suggests that each of these four dimensions may be related to semantic processing. For instance, there is evidence of faster recognition of animate objects than inanimate objects (Proverbio, Del Zotto, & Zani, 2007), and of better memory for words referring to animate concepts than words referring to inanimate concepts (e.g., Bonin, Gelin, & Bugaiska, 2014). There is also evidence that words referring to large objects are recognized faster than words referring to small objects (Sereno, O'Donnell, & Sereno, 2009) but at the same time there is evidence that object size does not affect word recognition (Kang, Yap, Tse, & Kurby, 2011). Effects of danger, usefulness, and their interactions with BOI have been characterized in recent studies by Wurm and colleagues (e.g., Van Havermaet & Wurm, 2014; 2017; Wurm, 2007; Wurm & Seaman, 2008). While some dangerous objects are frequent targets of interaction, it seemed possible that the caution required when interacting with such objects might lead to lower BOI values since those assess relative "ease" of interaction. We included each of these variables in the present study in order to assess their relationships with BOI, and to allow us to examine effects of the candidate motor dimensions independent of these other non-motor factors.

Present Study

Here we investigated several semantic dimensions that could be related to BOI effects observed in lexical-semantic processing, focusing in particular on the motor dimensions described by Guérard et al. (2015) as influential for object recognition. We collected new ratings so that we could examine effects for *word* stimuli. Our stimuli were 621 words that had been previously rated for BOI (Bennett et al., 2011; Tillotson et al., 2008). We used hierarchical regression analyses to examine relationships between our candidate dimensions and BOI ratings. We then examined whether our candidate dimensions predicted variance in semantic decision behaviour using response data from the Calgary Semantic Decision Project (Calgary SDT, Pexman, Heard, Lloyd, & Yap, 2017). In the Calgary SDT the decision category was "is it concrete or abstract?". We chose the behavioural data from this task to examine effects of the candidate motor dimensions because in this task a relatively large amount of variance is explained by semantic variables (Pexman et al., 2017). Less variance is typically explained by semantic variables in the lexical decision task (LDT; see Pexman, 2012, for a review), but because the LDT is so widely used, we also examined whether our candidate dimensions predicted variance in LDT behaviour using response data from the English Lexicon Project (Balota et al., 2007). We predicted that the semantic variables would account for less variance in LDT than SDT.

If a single motor dimension underlies the BOI dimension, then a significant amount of unique variance in BOI ratings should be predicted by ratings on that motor dimension. If multiple motor dimensions underlie the BOI dimension, then ratings on several motor dimensions should significantly predict variance in BOI ratings. Lastly, the motor dimension(s) found to predict unique variance in BOI ratings will likely also predict SDT and LDT response behaviour, and may be a stronger predictor of SDT and/or LDT behaviour than is BOI.

Method

Participants

A total of 490 participants were recruited for the ratings task. All participants were undergraduate students at the University of Calgary who received partial course credit in exchange for participation. Each participant provided ratings on one of the seven ratings scales for half of the stimuli, with 70 participants assigned to each rating scale (35 to each half of the stimuli). A total of 23 participants did not complete their assigned survey. In addition, participants' data were removed before analyses if (1) they provided the same rating for more than seven words consecutively (graspability: 1; ease of pantomime: 0; number of actions: 1; animacy: 2; size: 1; danger: 4; usefulness: 1) or (2) their overall mean rating was more than two standard deviations from the group mean (graspability: 6; ease of pantomime: 3; number of actions: 4; animacy: 3; size: 3; danger: 6; usefulness: 1). Resulting group sizes for each semantic dimension (for each half of the stimuli; see below) were as follows: graspability (29 and 29), ease of pantomime (29 and 32), number of actions (28 and 33), animacy (31 and 29), size (31 and 34), danger (29 and 32), and usefulness (35 and 30).

Stimuli

The stimuli were 621 words from the Tillotson et al. (2008) and Bennett et al. (2011) BOI norms that were also included as stimuli in the Calgary SDT (Pexman et al., 2017) and English Lexicon (Balota et al., 2007) Projects. Stimuli were divided into two lists consisting of 311 and 310 words such that the two lists were matched for mean BOI rating (3.57 and 3.58, respectively). Descriptive characteristics for these stimuli can be found in Table 1.

Procedure

The two stimuli lists were used to make two versions of an online questionnaire for ratings on each of the seven semantic dimensions; these 14 online questionnaires were created using Qualtrics. On each ratings questionnaire, words were presented in random order, 30 to a screen, with the relevant rating scale presented below each word. The ratings instructions are described in brief here and full versions of the ratings instructions for each semantic dimension are available in the Appendix. For ratings of graspability, ease of pantomime, and number of actions, scale anchors were adapted from those used by Guérard et al. (2015). For ratings of danger and usefulness, scale anchors were adapted from those used by Wurm (2007).

Graspability. Participants were asked to rate how easily each word's referent could be grasped using one hand from 1-7 (1 = cannot be grasped; 7 = very graspable).

Ease of pantomime. Participants were asked to rate how easily each word's referent can be pantomimed from 1-7 (1 = difficult; 7 = easy).

Number of actions. Participants were asked to rate the number of actions that can typically be performed with a word's referent from 0 (no actions) to 6+ (more than six actions).

Animacy. Participants were asked to rate how alive and capable of self-propelled motion each word's referent is from 1-7 (1 = inanimate; 7 = animate).

Size. Participants were asked to rate the size of a word's referent from 1-7 (1 = very small; 7 = very large).

Danger. Participants were asked to rate how dangerous a word's referent is for human survival from 1-7 (1 = not at all dangerous; 7 = extremely dangerous).

Usefulness. Participants were asked to rate how useful a word's referent is for human survival from 1-7 (1 = not at all useful; 7 = extremely useful).

Results

Mean ratings and standard deviations for all 621 words for each of the seven semantic ratings dimensions are available at https://osf.io/4jrcf/. The distributions for each of the seven semantic ratings dimensions are presented in Figure 1. The semantic variable Danger showed positive skew (1.97) and so was log10 transformed.

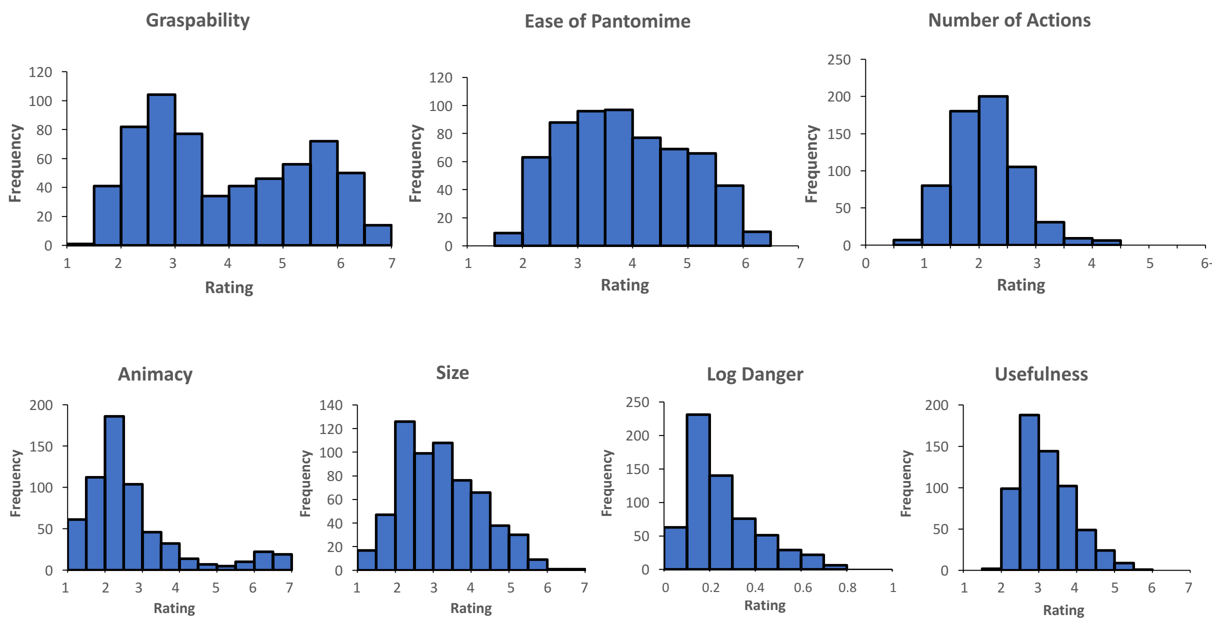

Figure 1. Distributions for semantic variable ratings. Histograms for each semantic variable are depicted. The *x*-axes depict the full range of each rating scale (1-7; number of actions 0-6+) and the *y*-axes depict the frequency of items within each rating bin. Bins were created for each 0.5 increment of the rating scale.

To explore relationships between the seven semantic ratings dimensions, BOI, and SDT and LDT performance, we conducted six main analyses. In the first regression analysis we examined the extent to which the semantic dimensions predicted BOI ratings, after controlling for lexical factors that could also influence BOI ratings. In the second and third analyses we examined the extent to which the semantic dimensions predicted SDT response latencies and SDT response accuracy, again after controlling for lexical factors that usually influence SDT performance. In the fourth and fifth analyses we examined the extent to which semantic dimensions predicted LDT response latencies and LDT response accuracy, again after controlling for lexical factors that usually influence LDT performance. Finally, we conducted analyses to examine whether BOI or the three candidate motor dimensions were better predictors of lexical-semantic processing.

The variables used in the analyses were divided into two clusters: lexical control variables and semantic dimensions. Lexical control variables were those that have been shown to be the most important non-semantic predictors of lexical and semantic decision performance: word length (Balota et al., 2007), and frequency (log transformed SUBTL word frequency; Brysbaert & New, 2009). Semantic dimensions included BOI (Bennett et al., 2011; Tillotson et al., 2008), our collected ratings: graspability, ease of pantomime, number of actions (Guérard et al., 2015), animacy (Amsel et al., 2012), size, danger and usefulness (Wurm, 2007) and age of acquisition (AOA, Kuperman, Stadthagen-Gonzalez & Brysbaert, 2012). We included AOA because AOA has been previously shown to be related to BOI (Connell & Lynott, 2016). That is, high BOI words tend to be acquired earlier than low BOI words (Thill & Twomey, 2016). Descriptive characteristics for each of these variables are presented in Table 1. AOA ratings (Kuperman et al., 2012) were not available for two words and lexical decision data was not available for one word, so we used a final set of 618 words for the analyses of BOI ratings and LDT response data. For the analyses of SDT response data we further restricted the item list to the 521 words that received “concrete” responses in the Calgary Semantic Decision Project data. We did not include in our analyses the 97 words that received “abstract” responses in that dataset because past research has shown that concrete and abstract words have some distinct relationships with semantic dimensions (Pexman et al., 2017; Pexman & Yap, in press).

Table 1

Mean descriptive statistics (standard deviations in parentheses) for 618 stimuli included in BOI and LDT analyses and 521 stimuli included in SDT analyses

Variable	Mean (n = 618)	Mean (n = 521)
Length	6.02 (1.92)	6.31 (1.93)
Log Frequency	2.31 (0.75)	2.29 (0.75)
Graspability	3.39 (1.48)	4.22 (1.41)
Ease of Pantomime	3.84 (1.10)	4.03 (1.06)
Number of Actions	2.12 (0.61)	2.21 (0.59)
Animacy	2.73 (1.32)	2.78 (1.42)
Size	3.19 (1.05)	3.08 (1.06)
Log Danger	0.25 (0.16)	0.25 (0.16)
Usefulness	3.18 (0.70)	3.21 (0.70)
Age of Acquisition (AOA)	7.62 (2.47)	7.26 (2.34)
Body-object Interaction (BOI)	3.57 (1.39)	3.93 (1.21)
SDT Latency (ms)	--	872.40 (113.37)
SDT Accuracy	--	92.51 (10.16)
LDT Latency (ms)	691.85 (86.63)	--
LDT Accuracy	91.20 (12.11)	--

Note. SDT = Semantic Decision Task; LDT = Lexical Decision Task.

Correlations between all variables are presented in Table 2. The semantic dimension most highly correlated with BOI ratings was graspability. In addition, the correlation between graspability and size was relatively high, with smaller objects rated as easier to grasp. Relationships between the other semantic dimensions were modest, suggesting that each dimension captures slightly different aspects of meaning.

Table 2

Correlations between predictor variables and dependent measures

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Length	---													
2. Log Frequency	-.17***	---												
3. Graspability	.25***	.00	---											
4. Ease of Pantomime	.27***	.38***	.33***	---										
5. Number of Actions	.01	.67***	.19***	.37***	---									
6. Animacy	-.07	.11*	-.07	.08	.11*	---								
7. Size	.07	.29***	-.67***	.03	.18***	.04	---							
8. Log Danger	.05	.15**	-.23***	.27***	.08	.23***	.35***	---						
9. Usefulness	.11*	.38***	.12**	.41***	.45***	.15***	.20***	.55***	---					
10. AOA	-.08	-.50***	-.31***	-.56***	-.49***	-.20***	.04	.02	-.32***	---				
11. BOI Rating	.17***	.26***	.68***	.43***	.40***	-.22***	-.35***	-.15***	.21***	-.38***	---			
12. SDT Latency	-.09*	-.37***	-.38***	-.48***	-.47***	-.20***	.04	-.07	-.33***	.59***	-.41***	---		
13. SDT Accuracy	.26***	.23***	.40***	.48***	.41***	.11*	-.05	.06	.30***	-.48***	.47***	-.60***	---	
14. LDT Latency	.31***	-.61***	-.03	-.28***	-.46***	-.09*	-.10*	-.07	-.27***	.43***	-.22***	.36***	-.21***	
15. LDT Accuracy	.17***	.50***	.21***	.42***	.47***	.08	.12**	.07	.30***	-.53***	.30***	-.47***	.45***	-.53***

Note. AOA = age of acquisition; BOI = body-object interaction; SDT = Semantic Decision Task; LDT = Lexical Decision Task. Correlations are depicted for the 521 items included in the analyses of SDT responses. * $p < .05$; ** $p < .01$; *** $p < .001$

Hierarchical Regression Analyses

Regression 1: BOI Ratings. Control variables were entered in step 1 and semantic dimensions were entered in step 2 of a hierarchical regression with BOI ratings as the dependent variable. Results of the regression analysis are presented in Table 3. Both length and frequency were significant predictors of BOI ratings, with higher BOI ratings for longer, more frequent words. Together, the semantic dimensions accounted for a significant amount of variance in BOI ratings. Significant, unique relationships were observed for graspability, ease of pantomime, number of actions, and animacy. That is, BOI ratings were higher for words with referents that are easier to grasp, easier to pantomime, afford more actions, and are less animate. Relationships between BOI and AOA, danger, and usefulness were not significant.

Table 3

Regression coefficients from item-level regression analyses for BOI ratings

Variable	*B*	*SEB*	*β*	R^2	ΔR^2
Step 1 (Control variables)				.16***	.16***
Length	0.27	0.03	.37***		
Log Frequency	0.42	0.07	.23***		
Step 2 (Semantic variables)				.69***	.53***
Graspability	0.48	0.04	.51***		
Ease of Pantomime	0.24	0.04	.19***		
Number of Actions	0.64	0.08	.28***		
Animacy	-0.17	0.03	-.16***		
Size	-0.08	0.05	-.06		
Log Danger	-0.23	0.27	-.03		
Usefulness	-0.04	0.06	-.02		
AOA	-0.01	0.02	-.03		

* $p < .05$; ** $p < .01$; *** $p < .001$

Regression 2: SDT Response Latencies. Lexical control variables were entered in step 1 and semantic dimensions in step 2 of a hierarchical regression analysis with SDT response latencies as the dependent variable. The regression results are presented in Table 4. Both length and frequency were significant predictor of SDT response latencies, with faster latencies for longer, more frequent words. The semantic dimensions predicted a significant amount of additional variance. Significant relationships were observed for graspability, ease of pantomime, number of actions, animacy, size, AOA, and BOI. More specifically, SDT latencies were faster for words with referents that are easier to grasp, easier to pantomime, afford more actions, are more animate, larger in size, acquired earlier in life, and high in body-object interaction. The relationships between SDT latencies and danger and usefulness were not significant.

Table 4

Regression coefficients from item-level regression analyses for SDT latencies

Variable	*B*	*SEB*	*β*	R^2	ΔR^2
Step 1 (Control variables)				.16***	.16***
Length	-9.43	2.40	-.16***		
Log Frequency	-60.48	6.17	-.40***		
Step 2 (Semantic variables)				.47***	.31***
Graspability	-23.50	5.13	-.29***		
Ease of Pantomime	-10.88	4.94	-.10*		
Number of Actions	-25.23	9.61	-.13**		
Animacy	-11.39	2.88	-.14***		
Size	-19.35	5.98	-.18**		
Log Danger	-21.43	32.52	-.03		
Usefulness	-0.74	7.49	-.01		
AOA	16.42	2.23	.34***		
BOI	-10.48	4.84	-.11*		

* $p < .05$; ** $p < .01$; *** $p < .001$

Regression 3: SDT Accuracy. Control variables were entered in step 1 and semantic dimensions in step 2 of a hierarchical regression analysis with SDT response accuracies as the dependent variable. The regression results are presented in Table 5. Both length and frequency were significant predictors of SDT response accuracy, with greater accuracy for longer, more frequent words. The semantic dimensions predicted a significant amount of additional variance. Significant relationships were observed for graspability, ease of pantomime, number of actions, animacy, size, AOA, and BOI. That is, SDT responses were more accurate for words with referents that are easier to grasp, easier to pantomime, afford more actions, are more animate, are larger in size, acquired earlier in life, and have higher body-object interaction. The relationships between SDT accuracy and danger and usefulness were not significant.

For both SDT response latencies and accuracy, parallel analyses were also conducted on trial-level data using a linear mixed effects approach. These analyses yielded comparable results to our hierarchical regressions. That is, the same significant relationships observed in the hierarchical regression analyses were also observed using linear mixed effects analyses.

Table 5

Regression coefficients from item-level regression analyses for SDT accuracy

Variable	B	SEB	β	R^2	ΔR^2
Step 1 (Control variables)				.14***	.14***
Length	0.02	0.00	.31***		
Log Frequency	0.04	0.01	.28***		
Step 2 (Semantic variables)				.42***	.28***
Graspability	0.01	0.01	.17*		
Ease of Pantomime	0.01	0.01	.14**		
Number of Actions	0.03	0.01	.18**		
Animacy	0.01	0.00	.11**		
Size	0.01	0.01	.15*		
Log Danger	0.02	0.03	.03		
Usefulness	0.00	0.01	.01		
AOA	-0.01	0.00	-.23***		
BOI	0.02	0.01	.24***		

* $p < .05$; ** $p < .01$; *** $p < .001$

Regression 4: LDT Response Latencies. Lexical control variables were entered in step 1 and semantic dimensions in step 2 of a hierarchical regression analysis with LDT response latencies as the dependent variable. The regression results are presented in Table 6. Both length and frequency were significant predictors of LDT response latencies, with faster latencies for shorter, more frequent words. The semantic dimensions predicted a significant amount of additional variance although, as expected, much less than they explained in the analysis of SDT latencies. A significant relationship was observed only for AOA, in that LDT latencies were faster for words that are acquired earlier in life. The relationships between LDT latencies and graspability, ease of pantomime, number of actions, animacy, size, danger, usefulness, and BOI were not significant.

Table 6

Regression coefficients from item-level regression analyses for LDT latencies

Variable	*B*	*SEB*	*β*	R^2	ΔR^2
Step 1 (Control variables)				.41***	.41***
Length	9.42	1.42	.21***		
Log Frequency	-66.04	3.62	-.57***		
Step 2 (Semantic variables)				.45***	.04***
Graspability	-0.23	3.72	-.00		
Ease of Pantomime	-3.83	3.61	-.05		
Number of Actions	-8.00	6.84	-.06		
Animacy	1.82	2.18	.03		
Size	-2.28	4.30	-.03		
Log Danger	7.30	22.58	.01		
Usefulness	-8.50	5.30	-.07		
AOA	5.67	1.60	.16***		
BOI	0.13	3.38	.00		

* $p < .05$; ** $p < .01$; *** $p < .001$

Regression 5: LDT Accuracy. Control variables were entered in step 1 and semantic dimensions in step 2 of a hierarchical regression analysis with LDT response accuracies as the dependent variable. The regression results are presented in Table 7. Both length and frequency were significant predictors of LDT response accuracy, with greater accuracy for longer, more frequent words. The semantic dimensions predicted a significant amount of additional variance. Significant relationships were observed for graspability, size, and AOA. That is, LDT responses were more accurate for words with referents that are easier to grasp, larger, and acquired earlier in life. The relationships between LDT accuracy and pantomime, number of actions, animacy, danger, usefulness, and BOI were not significant.

Table 7

Regression coefficients from item-level regression analyses for LDT accuracy

Variable	*B*	*SEB*	β	R^2	ΔR^2
Step 1 (Control variables)				.32***	.32***
Length	0.02	0.00	.27***		
Log Frequency	0.09	0.01	.54***		
Step 2 (Semantic variables)				.42***	.10***
Graspability	0.02	0.01	.23**		
Ease of Pantomime	0.01	0.01	.04		
Number of Actions	0.02	0.01	.10		
Animacy	-0.00	0.00	-.03		
Size	0.02	0.01	.18**		
Log Danger	0.02	0.03	.03		
Usefulness	-0.00	0.01	-.02		
AOA	-0.01	0.00	-.28***		
BOI	-0.01	0.01	-.08		

* $p < .05$; ** $p < .01$; *** $p < .001$

Regression 6: Comparative Analyses. We conducted one final set of analyses to compare the amount of variance in SDT and LDT behavioural performance explained by BOI with that explained by our three candidate motor dimensions (graspability, ease of pantomime, number of actions). Again, we entered lexical factors on step 1 of these analyses, and then entered BOI or the three candidate motor dimensions on step 2 of the analyses, along with AOA. We also calculated BIC values (Wagenmakers, 2007) in order to compare the effectiveness of the models containing the two different sets of predictors, for each dependent variable. The results of these analyses are presented in Table 8, with results for analyses of SDT latencies, SDT accuracy, LDT latencies, and LDT accuracy presented separately. BIC analyses show that for SDT latencies and accuracy, the models with the candidate motor dimensions together were more effective than the models with BOI. In contrast, for LDT latencies and accuracy, the models with BOI were more effective than the models with the candidate motor dimensions.

Table 8

Regression coefficients from item-level regression analyses comparing variance explained by BOI vs Motor Dimensions

	BOI						Motor Dimensions						
Variable	*B*	*SEB*	*β*	*sr*	R^2	ΔR^2	*B*	*SEB*	*β*	*sr*	R^2	ΔR^2	ΔBIC
SDT Latencies					.40***	.24***					.44***	.28***	-25.41
BOI	-19.61	3.53	-.21***	-.19									
Graspability							-14.91	2.98	-.19***	-.17			
Ease of Pantomime							-16.20	4.61	-.15***	-.12			
Number of Actions							-38.07	9.08	-.20***	-.14			
AOA	22.53	2.02	.46***	.38			17.04	2.17	.35***	.26			
SDT Accuracy					.36***	.21***					.38***	.24***	-12.14
BOI	.03	.00	.30***	.28									
Graspability							.01	.00	.18***	.16			
Ease of Pantomime							.02	.00	.21***	.16			
Number of Actions							.05	.01	.26***	.18			
AOA	-.02	.00	-.35***	-.29			-.01	.00	-.23***	-.17			
LDT Latencies					.45***	.04***					.46***	.04***	8.38
BOI	-4.73	2.62	-.07	-.06									
Graspability							-0.46	2.28	-.01	-.01			
Ease of Pantomime							-6.32	3.53	-.08	-.06			
Number of Actions							-12.96	6.95	-.09	-.06			
AOA	7.77	1.50	.21***	.17			6.50	1.66	.17***	.13			
LDT Accuracy					.40***	.09***					.40***	.09***	5.23
BOI	.01	.00	.06	.05									
Graspability							.00	.00	.04	.04			
Ease of Pantomime							.01	.01	.06	.05			

Number of Actions					.02	.01	.11*	.08
AOA	-.02	.00	-.32***	-.26	-.01	.00	-.28***	-.20

* $p < .05$; ** $p < .01$; *** $p < .001$

Note. ΔBIC was calculated using Wagenmakers' (2007) method for comparing non-nested models. Model 1 = BOI; Model 2 = graspability, ease of pantomime, and number of actions. Negative values indicate a lower BIC for model 2 indicating it is preferred over model 1. Positive values indicate a higher BIC for model 1 indicating it is preferred over model 2.

Discussion

The goal of the present study was to investigate which aspects of motor experience drive BOI effects in lexical-semantic processing. To do so, we collected ratings for 621 words on seven semantic dimensions, including three motor attributes (graspability, ease of pantomime, number of actions) and four other non-motor dimensions that we thought might be related to BOI (animacy, size, danger, usefulness). We found that the semantic dimension ratings collected in the present study could explain a considerable amount (53%) of the variance in the BOI ratings that were collected in previous studies (Bennett et al., 2011; Tillotson et al., 2008). Thus, the present findings offer some insights about factors that are related to BOI ratings. Graspability was the most significant predictor of BOI ratings, with high BOI concepts tending to be easier to grasp. This is presumably because upper-limb interactions are important to human motor behaviour and thus to the relative ease of our interactions with objects. Whereas graspability is based only on interactions of the hands with objects, BOI may also include interactions with other body parts. For instance, interactions of the feet with objects are likely important, as indicated by the moderately high BOI ratings for foot-related words like *stair* (5.23) and *step* (4.6). In addition, it seems likely that a more general bodily sense like that described by Borghi and Cimatti (2010) is also relevant. That is, a proprioceptive sense, involving an awareness of the body in place and time, may be part of what participants consider when they provide ratings of BOI. This might explain why words like *fire* and *shower*, which afford few opportunities for grasping, nonetheless receive moderate BOI ratings (4.27 and 4.33).

The seven semantic variables together explained a substantial amount of variance in SDT responses and, as expected, much less variance in LDT responses. SDT responses rely heavily on semantic processing, whereas LDT responses rely more heavily on lexical and orthographic processing (e.g., Pexman & Yap, in press; Taikh, Hargreaves, Yap, & Pexman, 2014; Yap et al., 2012). Indeed, the lexical control variables (length and frequency) explained considerably more variance in LDT performance than in SDT performance. Of the seven semantic variables, graspability was one of the two most consistent semantic predictors of lexical-semantic processing, as high graspability was associated with faster and more accurate SDT responses, and with more accurate LDT responses. The other consistent semantic predictor was size, but in a way that suggests it works in opposition to BOI. The zero-order correlations (Table 2) show that, as expected, size was negatively related to BOI. Words that refer to small objects tend to have higher BOI ratings. The analyses of lexical-semantic processing, however, showed that words that refer to *large* objects have faster and more accurate SDT responses, and more accurate LDT responses. These facilitory effects of referent object size are consistent with those reported by Sereno et al. (2009; cf. Kang et al., 2011). Sereno et al. attributed size effects to faster retrieval of visual representations for large objects than for small objects, and took such effects as evidence that sensorimotor information is automatically accessed when reading a word.

Similarly, the patterns observed for the animacy variable suggest that its effects also work in opposition to those of BOI. As expected, animacy was negatively related to BOI ratings, such that more animate objects tended to have lower BOI ratings; many animate objects (e.g., *tiger*, *rhinoceros*) do not afford easy interaction. In lexical-semantic processing, however, animacy facilitated responses: in SDT, responses were faster and more accurate for words referring to more animate objects. The present finding of an animacy effect in SDT extends the effects observed previously in other contexts, such as object recognition (Proverbio et al., 2007), and memory (e.g., Bonin et al., 2014). Animacy effects have been attributed to the survival advantage for these concepts (e.g., Nairne, 2010), in that animate objects play an important role in human survival, as both predators and prey. Thus, while size and animacy are related to BOI ratings, they are likely not drivers of the facilitory BOI effect observed in lexical-semantic processing.

Instead, our results suggest that, from among the variables we measured in the present study, the three motor dimensions are the most likely drivers of BOI effects in lexical-semantic processing. Further, the comparative analyses showed that these three variables are more effective than BOI at explaining variance in SDT, and somewhat less effective at explaining variance in LDT responses. We speculate that the candidate motor dimensions are particularly effective predictors in SDT because the concrete/abstract decision depends on extensive semantic processing and a strategy of focusing on tactile and tangible features (Hargreaves, White, Pexman, Pittman, & Goodyear, 2012). Specific dimensions of motor information better predict this more specific semantic processing in SDT. In contrast, in LDT the focus is largely on orthographic processing and while semantic processing is relevant it is less extensive and less specific. The single predictor of BOI is effective in that case.

Depending on their goals, researchers may want to use these more specific motor dimensions rather than BOI to examine whether particular aspects of motor information are accessed in language or cognitive tasks. For instance, in past research less-specific measures of motor-related attributes of functionality and manipulability have been examined and found to influence a variety of cognitive domains, including memory, attention, and semantic processing (e.g., Creem & Proffitt, 2001; Hauk, Johnsrude, & Pulvermüller, 2004; Just, Cherkassky, Aryal, & Mitchell, 2010; Madan & Singhal, 2012; Madan, 2014, 2017; Montefinese, Ambrosini, Fair eld, & Mammarella, 2012; Shebani & Pulvermüller, 2013). The ratings collected in the present study offer researchers the opportunity to investigate the contributions of motor information in a more fine-grained way, helping advance our understanding of the role that motor information plays in human cognition.

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Appendix

Written Instructions for the Graspability Rating Task

The referents that words refer to vary in terms of how graspable they are. Something that is graspable can be grasped using one hand whereas something that is not graspable cannot.

In this study your task is to rate each word's referent based on how graspable it is. Ratings will be made on a scale from 1 to 7. Any referent you believe not graspable should be rated as a 1 and any referent you believe to be very graspable should be rated a 7.

For example, the word 'beach' should be rated as a 1 since its referent cannot be grasped with one hand whereas the word 'scissors' should be rated as a 7 since its referent can easily be grasped with one hand.

When rating a referent, try to be as accurate as possible, but do not spend too much time on it.

1	2	3	4	5	6	7
Not Graspable						Very Graspable

Written Instructions for the Ease of Pantomime Rating Task

Objects differ in the extent to which a person can think of an action involving that object. For some objects it is easier to think of an action than for others. The purpose of the present experiment is to rate words regarding how easily a person could pantomime or act out the use of their referent (what the word is referring to).

In this case a pantomime is defined as a concept that can be expressed with a few simple gestures. For example, interactions with a "hammer" are probably quite easy to pantomime (eg. a downward swinging gesture). It is more difficult to pantomime interactions with a "ceiling".

Any referent that is easy to pantomime should be given a high rating. Any referent that is difficult to pantomime should be given a low rating. Your ratings will be made on a 1 to 7 scale, a value of 1 indicates that you think the referent is very difficult to pantomime and a value of 7 indicating that the referent is very easy to pantomime. Values of 2 to 6 indicate intermediate ratings. Click on the most appropriate value for each referent. When rating a referent, try to be as accurate as possible, but do not spend too much time on it.

1	2	3	4	5	6	7
Very difficult to Pantomime						Very Easy to Pantomime

Written Instructions for the Number of Actions Rating Task

Some objects can be used to perform multiple actions (e.g., a dog can be pet, brushed, hugged, etc.) while other objects can only be used for one particular action (e.g., chopsticks can be used for picking up food). For each word, your task is to estimate the number of actions that you can typically perform with the word's referent (what the word refers to). For each object, click on the value corresponding to the number of possible actions.

For example, "scissors" would probably have one action as it would typically be used to cut whereas "ball" would likely have multiple actions as it can be thrown, caught, kicked, etc.

**please note:* although it may be possible to use the word's referent for other actions (eg. using a screwdriver to hammer a nail) we ask that you rate the referent on the number of actions it would typically be used for.

Your ratings will be made on a 0 to 6+ scale. Any referent with 6 or more associated actions should be rated a 6+. When rating a referent, try to be as accurate as possible, but do not spend too much time on it.

0	1	2	3	4	5	6+
No Action						Many

Written Instructions for the Animacy Rating Task

The referents that words refer to vary in terms of whether they are animate or inanimate. An animate thing is something that is living and capable of self-propelled motion whereas an inanimate thing is something that is nonliving and incapable of self-propelled motion.

In this study your task is to rate the animacy of the word's referent. Ratings will be made on a scale from 1 to 7. Any referent you believe is completely inanimate should be rated a 1 and any referent you believe to be completely animate should be rated a 7.

For example, the word 'wall' should be rated as a 1 since its referent is completely inanimate whereas the word 'rabbit' should be rated as a 7 since its referent is completely animate.

When rating a referent, try to be as accurate as possible, but do not spend too much time on it.

1	2	3	4	5	6	7
Inanimate						Animate

Written Instructions for the Size Rating Task

The referents that words refer to greatly vary in size. In this study your task is to rate the size of the word's referent from very small to very large. Ratings will be made on a scale from 1 to 7.

Any referent you believe is very small should be rated a 1 and any referent you believe to be very large should be rated a 7.

For example, the word ‘pin’ should be rated as a 1 since its referent is very small whereas the word ‘Earth’ should be rated as a 7 since its referent is very large.

When rating a referent, try to be as accurate as possible, but do not spend too much time on it.

1	2	3	4	5	6	7
Small						Large

<u>Written Instructions for the Danger Rating Task</u>

We would like you to rate how dangerous for human survival you think each word’s referent is.

Your ratings will be made on a 1 to 7 scale, a value of 1 indicating that the referent is not at all dangerous to human survival and a value of 7 indicating that the referent is extremely dangerous for human survival. Values of 2 to 6 indicate intermediate ratings.

For example, the word ‘thief’ may be rated highly whereas the word ‘grape’ may be rated low.

There are no right or wrong answers -- it's up to you to decide. There are quite a few words, so don't spend a lot of time on each one. Just go with your first judgment.

A number line will appear on-screen for you to use in making your rating. Please use the rating options displayed below the word to indicate your choice.

1	2	3	4	5	6	7
Not at all Dangerous for human survival						Very Dangerous for human survival

<u>Written Instructions for the Usefulness Rating Task</u>

We would like you to rate how useful for human survival you think each word’s referent is.

Your ratings will be made on a 1 to 7 scale, a value of 1 indicating that the referent is not at all useful to human survival and a value of 7 indicating that the referent is extremely useful for human survival. Values of 2 to 6 indicate intermediate ratings.

For example, the word ‘grape’ may be rated highly whereas the word ‘ash’ may be rated low.

There are no right or wrong answers -- it's up to you to decide. There are quite a few words, so don't spend a lot of time on each one. Just go with your first judgment.

A number line will appear on-screen for you to use in making your rating. Please use the rating options displayed below the word to indicate your choice.

1	2	3	4	5	6	7
Not at all Useful for human survival						Very Useful for human survival