An embodied semantic processing effect on eye gaze during sentence reading

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Abstract

The present research examines the effects of body-object interaction (BOI) on eye gaze behaviour in a reading task. BOI measures perceptions of the ease with which a human body can physically interact with a word's referent. A set of high BOI words (e.g. cat) and a set of low BOI words (e.g. sun) were selected, matched on imageability and concreteness (as well as other lexical and semantic variables). Facilitatory BOI effects were observed: gaze durations and total fixation durations were shorter for high BOI words, and participants made fewer regressions to high BOI words. The results provide evidence of a BOI effect on non-manual responses and in a situation that taps normal reading processes. We discuss how the results (a) suggest that stored motor information (as measured by BOI ratings) is relevant to lexical semantics, and (b) are consistent with an embodied view of cognition (Wilson 2002).

Keywords
embodied cognition, sensorimotor knowledge, body-object interaction, eye-gaze, sentence processing

1. Introduction

Research on embodied cognition examines how interactions between the body and the environment influence the acquisition of knowledge and the

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development of cognitive processes that rely on that knowledge (Barsalou 1999; Clark 1997; Gibbs 2006; Kiefer and Pulvermüller In press; Lakoff and Johnson 1999; Pecher and Zwaan 2005; Wilson 2002). This is a departure from the traditional cognitive science approach that typically focuses on internal cognitive processes (e.g. Pylyshyn 1984). An important question for the embodied cognition perspective is whether cognitive processes and representations, such as those used for memory and reading, are grounded in the interactions humans have with the environment.

The embodied cognition perspective incorporates a number of claims with respect to how the mind, the body, and the surrounding environment interact to allow an organism to behave appropriately and adaptively (Wilson 2002). Two of these claims are especially relevant to the present research. The first is that the ultimate purpose of cognitive mechanisms, such as perception and memory, is to guide action so that we behave in a situation-appropriate manner. The second claim is that the same cognitive mechanisms that evolved to allow for situation-appropriate behaviors are used when cognition is decoupled from the environment (i.e. off-line). In her discussion of the latter claim, Wilson proposed that on-line cognitive processes that originally evolved to help the organism interact with its immediate environment may have been co-opted to deal with less direct interactions; the off-line use of these processes allows the organism to mentally simulate possible solutions to an environmental demand without actually performing each solution. For example, in Perceptual Symbols Theory, retrieving conceptual knowledge involves the simulation of the sensorimotor, emotional, and cognitive states that were involved during encoding (Barsalou 1999, 2003a, 2003b; Barsalou et al. 2003).

Consistent with this view, research has shown that sensory and motor areas that are involved during the acquisition of a concept are recruited during conceptual processing (Hoenig et al. 2011; Kiefer and Pulvermüller In press; Kiefer et al. 2007; Weisberg et al. 2007). For example, the auditory association cortex is activated when professional musicians, but not musical laypersons, are presented with visual images of musical instruments (Hoenig et al. 2011). This result indicates that the intensive auditory experience professional musicians have with musical instruments influences their conceptual representations. A similar pattern of results has been found following extensive training to use novel objects as tools (Weisberg et al. 2007). After training, the pattern of neural activity in response to images of the novel objects differed from that recorded before training and reflected the regions associated with motion and manipulation of common tools. These findings support the idea that the manner in which conceptual features are represented depends upon a person's bodily experiences. In the present study, the possibility that the conceptual knowledge one gains via past bodily experiences can be a source of information accessible during language processing was investigated.

One of the ways that embodied cognitive processes can be investigated is by using a response methodology that incorporates the sensorimotor activities that are proposed to be important for the required response. Glenberg and Kaschak's (2002) action-sentence compatibility effect is an example of this approach. In Glenberg and Kaschak's study, participants read sentences that implied a directional action either toward or away from the body (e.g. *Close the drawer.*) and judged whether the sentence was sensible or not by making a response that required an arm movement either toward or away from the body. Although response direction was irrelevant to the sensibility judgement, the direction of movement required for a response interacted with the direction of movement implied in the sentence: response times were fastest when the direction implied in the sentence was congruent with the action required to respond and slowest when the direction and action were incongruent. Glenberg and Kaschak concluded that merely processing the meaning of such sentences makes salient the spatial or functional information contained in the sentence, which in turn appears to affect the motor system (or vice versa).

An alternative approach to exploring the use of embodied cognitive processes off-line is to use a methodology that does not contrast congruent and incongruent sensorimotor activities. There are now a number of such studies in the literature, examining the effects of sensorimotor knowledge using visual object recognition tasks (Helbig et al. 2006; Helbig et al. 2010; Kiefer and Pulvermüller In press; Kiefer et al. 2011) and, more relevant to the focus of the present work, using word recognition tasks (Myung et al. 2006; Siakaluk, Pexman, Aguilera et al. 2008; Siakaluk, Pexman, Sears et al. 2008; Wellsby et al. 2011). For example, Myung et al. (2006) reported a priming effect of motor information on auditory word recognition; specifically, they reported faster lexical decision responses for words that were preceded by a word that shared manipulation features (e.g. piano-typewriter) than for words that were preceded by a word that did not share manipulation features (e.g. piano-bucket). This suggests that sensorimotor information was activated in the auditory priming paradigm and that this information is relevant to lexical semantics.

This possibility was further explored by Siakaluk, Pexman, Aguilera et al. (2008) and Siakaluk, Pexman, Sears et al. (2008) using ratings on a variable they called *body-object interaction* (BOI), which measures the perception of the ease with which a human body can physically interact with a word's referent. Siakaluk, Pexman, Aguilera et al. (2008) and Siakaluk, Pexman, Sears et al. (2008) selected a set of high BOI words (e.g. *belt*) and a set of low BOI words (e.g. *ship*) such that the sets of words were matched on imageability and concreteness (as well as other lexical and semantic variables). Facilitatory BOI effects were found using a standard lexical decision task (*Is this a word?*), a phonological lexical decision task (*Does it sound like a word?*), a semantic categorization task (*Is the word imageable?*), and a semantic lexical decision task (*Is it a word? If so, is it imageable?*). Participants were faster and more accurate when responding to high BOI words than to low BOI words in all of these tasks. Because the word sets were matched on a variety of lexical and semantic variables, most importantly imageability and concreteness, the authors attributed the facilitatory BOI effects to sensorimotor information that had been gained through previous bodily interactions with the word's referents and that was accessed in the process of visual word recognition.

BOI effects suggest that bodily experience is relevant to lexical semantics, and that words that are associated with relatively more bodily experience will be processed more readily than words that are associated with relatively less bodily experience. It has been argued that BOI effects are similar to a number of effects referred to as semantic richness effects (Pexman et al. 2008) whereby words associated with relatively more of some kind of semantic information (e.g. semantic features, semantic associates, semantic neighbours) are processed more readily in visual word recognition tasks (see Pexman et al. 2008; Yap et al. 2011, for reviews). These richness effects can be accommodated by the feedback activation framework of visual word recognition (Hino and Lupker 1996; Hino et al. 2002). This framework has several key assumptions, but most important for present purposes is the assumption that words that evoke richer semantic representations will experience faster semantic settling and also stronger feedback activation from the semantic units to the other units in the system (orthographic and phonological units). Facilitatory BOI effects are explained by the feedback activation framework as semantic richness effects, the key assumption being that sensorimotor information associated with high BOI words increases their semantic richness, which in turn facilitates their processing in a variety of tasks.

2. The present research

One limitation of the aforementioned BOI studies is that the measured behaviour was a manual response (e.g. the lexical decision task, the semantic categorization task). The concern with using manual responses to study off-line BOI effects is that it is possible that the facilitatory BOI effects that have been observed may have been, at least to some degree, the result of motor system priming. Certainly, there is other research evidence to show that action representations influence semantic processing in tasks that do not depend upon a motor response (Helbig et al. 2006; Kiefer et al. 2007). Further, Wellsby et al. (2011) evaluated BOI effects using a task that did not require manual responses; they reported a facilitatory BOI effect in semantic categorization task that used a verbal response ("yes" or "no" responses spoken aloud). Although Wellsby et al. acknowledged that a verbal response is a motor response, they argued that the motor programs associated with verbalizations are not strongly related to the motor programs associated with how people physically interact with objects. Together these results suggest that the effects found in BOI studies are not simply the result of motor system priming. Nevertheless, a stronger case could be made for this conclusion if a facilitatory BOI effect was also observed on non-manual responses. To be clear, this will not preclude the possibility that facilitatory BOI effects may involve activation of the motor system. The goal of the present research is to dissociate facilitatory BOI effects from simple motor system priming—not to dissociate the effects from motor system activation. In fact, some embodied cognition theories, such as simulation theory, propose that conceptual processing involves the partial re-instatement of sensory and motor activity during perception and action (Barsalou 1999, 2003a, 2003b; Barsalou et al. 2003; Kiefer and Pulvermüller In press). Thus, according to these theories lexical semantic processing will likely involve sensory and motor system activation.

An additional limitation of previous research is that BOI effects have thus far only been studied using tasks involving a decision component (typically with a motor response), such as the lexical decision task and the semantic categorization task. Unlike the normal reading situation, in all of these tasks participants respond to single words presented in isolation. Although the action-sentence compatibility effect involves sentence processing, the effects of prior bodily experience (as measured by BOI) have not yet been studied in the context of sentences. Thus, we do not yet know whether prior bodily experience influences more incidental language processing (where a lexical or semantic decision is not required, and where there is context provided for the high and low BOI words). In the present experiment, the effect of BOI on the reading of target words embedded in sentence contexts was examined using eye movement monitoring. Our experiment builds and expands on the research of Wellsby et al. (2011) and others by looking for evidence of BOI effects on non-manual responses and in a situation that taps normal reading processes. We selected items such that the high BOI words were matched to the low BOI words for both imageability and concreteness as well as several other lexical and semantic variables. Therefore, any effects of BOI on eye gaze should be attributable to sensorimotor information that has been gained through prior bodily interactions with the word referents. If embodied effects extend to incidental, contextualized language processing then we should observe facilitatory BOI effects on reading times, as indexed by eye gaze behavior.

2.1. *Method*

2.1.1. *Participants.* The participants were 75 (64 female) University of Calgary undergraduate students (M = 22.55 years, SD = 6.19) who volunteered in exchange for extra course credit. Participants self-identified as native speakers of English and reported normal or corrected-to-normal vision.

2.1.2. *Stimuli.* The critical stimuli were 40 pairs of words (e.g. *sun–cat*; see Appendix) that were matched on length. Each pair consisted of one word with a high BOI rating ($M = 5.63$, $SD = 0.44$) and the other with a low BOI rating ($M = 3.33$, $SD = 0.59$), $t(78) = 19.75$, $p < .001$, according to the BOI ratings collected by Tillotson et al. (2008). The high and low BOI word sets did not differ in mean normative frequency (Kucera and Francis 1967), $t(78) = 0.57$, $p = .57$, CELEX normative frequency (Davis 2005), $t(50.35) = 1.10$, $p = .28$, the standard frequency index from the Educator's Word Frequency Guide (Zeno et al. 1995), $t(53.78) = 1.26$, $p = .21$, familiarity (Wilson 1988), $t(78) = 0.74$, $p = .47$, concreteness (Wilson 1988), $t(78) = 1.22$, $p = .23$, imageability (Wilson 1988), $t(78) = 0.40$, $p = .69$, bigram frequency (Balota et al. 2007), $t(78) = 0.27$, $p = .79$, number of orthographic neighbors (Balota et al. 2007), $t(78) = 0.04$, $p = .97$, or contextual dispersion (Zeno et al. 1995), $t(78) = 1.14$, $p = .26$. Means and standard deviations for each of these variables are reported in Table 1. In addition, subjective frequency ratings were collected from a separate group of 38 University of Calgary undergraduates (none of whom participated in the experiment). They were asked to estimate how frequently they encountered the 80 high and low BOI words in print using a scale from 1 (*very infrequently*) to 9 (*very frequently*). The mean subjective frequency ratings for the high and low BOI word sets did not differ, $t(78) = 1.32$, $p = .19$.

Forty sentence frames, one for each pair of high and low BOI words, were created to embed the target words. For example, for the pair gang/mate, the sentence frame was "*Alexander secretly thought that his [gang/mate] was*

Table 1. *Mean characteristics and standard deviations for high and low BOI stimuli*

	High BOI		Low BOI	
	M	*SD*	*M*	*SD*
Length	4.08	0.76	4.08	0.76
Kucera and Francis (1967) print frequency	3.09	1.15	3.26	1.55
CELEX word frequency	63.44	113.31	118.17	293.78
Subjective frequency	4.78	1.23	4.38	1.50
Standard frequency index	54.37	3.96	52.42	8.92
Mean bigram frequency	1654.08	875.75	1705.32	835.97
Number of orthographic neighbors	9.58	6.33	9.63	5.10
Familiarity	537.08	43.69	529.73	45.78
Concreteness	569.78	47.35	557.35	43.69
Imageability	564.90	46.25	560.63	49.06
Contextual dispersion	0.74	0.13	0.70	0.17

behaving strangely". (The 40 sentence frames are listed in the Appendix.) The maximum sentence length was 80 characters (including spaces). Using the same sentence frame for each word pair had a number of advantanges, the most important being that the sentence context for both target words was identical. To ensure that the high and low BOI targets did not differ in terms of their predictability and contextual congruency within their sentence frames, additional rating data were collected.

To assess how predictable the target words were within the sentence frames, 38 undergraduate students from the University of Calgary (the same students who provided the subjective frequency ratings) were asked to provide the missing word that they thought best fit in each frame (e.g. *Judith saw the reflection of the ____ in the oval mirror*). The target words were seldom given as responses in this cloze task, and the percentage of high BOI target words provided (0.66%) was statistically equivalent to the percentage of low BOI target words provided (0.33%), $t(39) = 0.90$, $p = .38$. The target that was produced most frequently for its sentence frame was *goat*; it was produced by 3 of the 38 participants. The majority of target words (72; 90.0%) were never given as responses, reflecting the fact that the high and low BOI targets were of uniformly low predictability.

To assess how contextually congruent the target words were within the sentence frames, another group of 56 undergraduate students from the University of Calgary were asked to select which of the target words best fit the sentence frame. The presentation order of the high and low BOI word options for each frame was randomized for each participant. In this task the at-chance preference for either high or low BOI words would be 50%; the results showed that high BOI words were not selected at a rate that differed from chance (52.77%), $t(39) = 0.61$, $p = .54$.

To further assess how contextually congruent the target words were within the sentence frames, another group of 36 students from the University of Calgary was asked to rate how well the target word fit the sentence frame on a scale from 1 to 7, where 1 represented a very poor fit and 7 represented an excellent fit. Participants saw either the low or high BOI target of each pair, embedded in their sentence frames. Ratings for high BOI words ($M = 5.71$, $SD = 0.78$) were not significantly different than those for low BOI words ($M = 5.43$, $SD = 0.93$), $t(39) = 1.56$, $p = .13$, which indicates that the high and low BOI targets were equally contextually congruent with their sentence frames.

2.1.3. *Apparatus and procedure.* Eye movements were recorded by an EyeLink I eye tracking system (SR Research Ltd., Mississauga, Ontario, Canada). Participants wore a small, lightweight headband equipped with cameras positioned below the eyes that tracked pupil position. The system has an average gaze error of less than 0.5 degrees and a sampling rate of 250 Hz (allowing for a temporal resolution of 4 ms). The EyeLink system compensates for small changes in head position during tracking so a head rest is not necessary. The eye-tracking system was connected to a Dell Dimension 8300 computer and a ViewSonic G225fb 21-inch flat-screen monitor with a vertical retrace rate of 160 Hz. The computer controlled the visual display and recorded the horizontal and vertical co-ordinates corresponding to the position of the right eye every 4 ms continuously during each trial.

Each sentence was presented in a single row in the computer display. The sentences were presented in white Calibri 18 point font on a black background. The words in each sentence were presented in lower case letters, with the exception of the first letter of the first word of each sentence and proper names. The target word was always in the second half of the sentence and was at least one word ($M = 3.35$ words, $SD = 0.92$) from the end of the sentence.

At the start of the session participants were fitted with the headband and the eye-tracking system was calibrated. The calibration process required approximately five minutes. A trial sequence was as follows. First, participants were asked to fixate on a dot presented in the middle of the computer display (the drift correction screen). When the participant's eye gaze stabilized on the dot, the experimenter triggered the sentence presentation. An asterisk was presented on the far left of the computer display for 500 ms (to direct attention to the start of the sentence), followed by the sentence, which was presented in the centre of the display. Participants were instructed to read each sentence silently for meaning; they were informed that their comprehension of the sentences would be tested occasionally. After they had finished reading the sentence they were to look at the bottom of the display and press a mouse button to indicate they had finished reading. The mouse click triggered presentation of the next drift correction screen. Participants read ten practice sentences and answered one comprehension question to familiarize themselves with the procedure prior to the experimental trials. During the experimental trials, a comprehension question followed five of the sentences (randomly selected). Accuracy in answering these comprehension questions was very high (93%). One participant answered fewer than 50% of the comprehension questions correctly and was excluded from all analyses.

2.1.4. *Design.* Each participant was presented with one of two lists of low and high BOI target words embedded in the sentence frames. Each list consisted of one word from each of the forty pairs of words, such that there were twenty sentences with low BOI target words and twenty sentences with high BOI target words. Thus, each participant saw only one presentation of each sentence frame. The target words used in the two lists (see Table 2) did not differ significantly on any of the stimulus characteristics described above (all $ps > .35$).

Table 2. *Mean characteristics and standard deviations for list 1 and list 2*

	High BOI		Low BOI	
	M	*SD*	*M*	*SD*
BOI	4.43	1.35	4.53	1.18
Length	4.08	0.76	4.08	0.76
Kucera and Francis (1967) print frequency	3.03	1.43	3.31	1.28
CELEX word frequency	91.53	216.92	90.09	231.58
Subjective frequency	4.69	1.23	4.47	1.38
Standard frequency index	53.12	7.15	53.68	6.78
Mean bigram frequency	1732.63	760.37	1585.83	888.22
Number of orthographic neighbors	9.60	5.63	9.60	5.86
Familiarity	533.35	45.41	533.45	44.40
Concreteness	562.48	43.42	564.65	48.40
Imageability	561.85	49.29	563.68	46.09
Contextual dispersion	0.72	0.16	0.71	0.15

Data analyses included the following variables for the target region (the target region was defined as the space occupied by the target word): first fixation duration (duration of the first fixation in the target region), gaze duration (the sum of the fixation durations in the target region before the reader left the target region), total fixation duration in the target region (the sum of fixation durations in the target region, including fixations following regressions), and the percentage of trials in which the target word was initially skipped. Analyses also included spillover effects—or the processing that occurred after the participant left the target region, assessed by the duration of the first fixation after leaving the target word—the percentage of trials on which a regression back to the target word was made, and the total time spent in the post-target region (the post-target region was defined as the space occupied by the two words following the target word, as many of the target words were followed by a function word).

2.2. *Results*

Consistent with standard practices in eye movement research (e.g. Pollatsek et al. 1999; Rayner 1998), trials in which the participant skipped the target were excluded from the analysis; a total of 466 trials (15.74%) were excluded because of skipping. In addition, trials in which the participant physically moved during the trial ($n = 10$), returned to the sentence after looking to the bottom of the screen ($n = 103$), started reading in the middle of the sentence ($n = 1$), fully re-read the sentence at least once (indicative of not understanding the sentence on the first reading; $n = 173$), or trials in which there were tracking issues (e.g. a lateral shift as a result of an incorrect drift correction, gaps in

Table 3. *Mean response measures and standard deviations as a function of target word BOI*

	High BOI		Low BOI	
	M	*SD*	*M*	*SD*
First fixation duration	243.12	38.75	248.96	41.48
Gaze duration	256.52	38.80	265.03	42.06
Total fixation duration*	312.97	65.55	345.92	84.73
Percentage skipped	20.0	14.0	19.0	14.0
Percentage regressed*	26.0	18.0	32.0	19.0
First fixation duration in post-target region	256.63	64.93	258.57	57.80
Total time spent in post-target region	448.29	166.38	460.71	156.20

* $p < .05$
Note. Means are from the subject analysis.

the tracking of eye movements; $n = 250$) were discarded. A total of 537 trials (18.14%) were excluded from all analyses for these reasons. These criteria were motivated by a desire to include only those trials in which the participant was reading normally, understood the sentence as reading progressed, and read the target the first time it was encountered. These criteria are especially important because two of our measures of interest, first fixation duration and gaze duration, require fixation on the target during the first reading and are especially sensitive to reading progression. The final data set consisted of data from 74 participants with a total of 1003 trials (33.89%) excluded, of which approximately one quarter of the trials (8.45%) were excluded due to tracking issues.

The dependent variables (see Table 3) were analyzed by subjects ($t1$) and by items ($t2$) using paired samples t-tests. Trials with target word gaze durations greater than three standard deviations above the mean were trimmed (38 trials, 1.94% of the data).

There was no significant difference between high and low BOI words for first fixation duration, $t1(73) = 1.30$, $p = .20$; $t2(39) = 1.50$, $p = .14$, or percentage of trials in which the target was skipped, $t1(73) = 0.78$, $p = .44$; $t2(39) = 0.81$, $p = .42$. There was, however, a significant difference between high and low BOI words for gaze duration in the item analysis, $t2(39) = 2.15$, $p = .04$, which was marginally significant in the subject analysis, t1(73) = 1.95, p = .06. As can be seen in Table 3, gaze durations for high BOI words were 8.51 ms shorter than those for low BOI words. Similarly, there was a significant difference between high and low BOI words for total fixation duration, $t1(73) = 4.18$, $p < .001$; $t2(39) = 2.52$, $p = .02$. Total fixation durations to high BOI words were 32.95 ms shorter than those for low BOI words. These results indicate that the high BOI words were read faster than the low BOI words, consistent with the facilitory BOI effects observed in manual response latency tasks (e.g. Siakaluk, Pexman, Aguilera et al. 2008; Siakaluk, Pexman, Sears et al. 2008).

For spillover effects, there was no significant difference between high and low BOI words for the first fixation duration in the post-target region, $t1(73) = 0.28$, $p = .78$; $t2(39) = 0.30$, $p = .76$, or the total fixation duration in the post-target region, $t1(73) = 0.67$, $p = .51$; $t2(39) = 1.24$, $p = .22$. There was, however, a significant difference between high and low BOI words in the percentage of trials in which a regression back to the target was made, $t1(73) = 2.56$, $p = .01$; $t2(39) = 1.83$, $p = .08$. Participants made more regressions to low BOI target words (32%) than to high BOI target words (26%), which is consistent with the longer gaze durations and total fixation durations for the low BOI words.

3. Discussion

The purpose of this study was to determine whether sensorimotor information, as measured by BOI, influences the reading times of words embedded in sentences. Consistent with previous research that used tasks that measured manual responses, we observed a facilitatory BOI effect—participants made fewer regressions to high BOI words and spent less time fixated on high BOI words when silently reading sentences for comprehension, both on the first reading of the target (gaze duration) and in the total time spent reading the target (total fixation duration). Because high and low BOI words were matched on many lexical and semantic variables and fit equally well into the sentence frames, the most straightforward interpretation of the observed BOI effect is that it is due to the additional sensorimotor information associated with high BOI words. High BOI words are associated with relatively more sensorimotor information, and this richness facilitated reading. This effect of BOI on incidental, contextualized language processing further supports the idea that prior bodily experience is relevant to lexical semantics.

The present findings are a further demonstration of semantic influences on the reading times for words presented in neutral sentence contexts. Juhasz and Rayner (2003) examined the effects of another semantic variable (concreteness) using eye gaze measures and reported that concreteness was a significant predictor of gaze duration and total fixation duration while reading neutral sentences. Juhasz and Rayner concluded that concreteness influenced refixation and re-reading processes (rather than earlier processes, such as those that influence first fixations). Interestingly, a similar type of effect involving later processes was observed for the present semantic manipulation, with fewer regressions and shorter total fixation durations to high BOI words. Juhasz and Rayner's results, like our results, support the idea that semantic richness effects generalize to reading in sentence contexts.

Our design involved word pairs and (across participants) the presentation of both words in the identical sentence frames. With these designs, there is often a concern that observed differences in target word processing could be attributed to differences in contextual fit. As noted previously, however, this explanation is unlikely to account for our data. That is, data from three separate groups of undergraduates showed that: (i) the high and low BOI target words were selected as fitting within the sentence frames with equal probability, (ii) high and low BOI words were rated as fitting the sentence frames equally well, and (iii) the high and low BOI target words were equally predictable within their sentence frames and were both very seldom given as a response in a cloze task. Together these analyses confirm that the high and low BOI words fit into the sentence frames equally well and were equally predictable, which makes it very unlikely that the differences in reading times for low and high BOI target words were due to confounds in the materials used in this study. Nevertheless, a replication by different researchers using different materials would be ideal.

The relatively late effects of BOI on reading observed here can be accommodated by the E-Z Reader model of eye movement control in reading (Pollatsek et al. 2008; Pollatsek et al. 2006; Reichle et al. 2009) and the feedback activation framework of visual word recognition (Hino and Lupker 1996; Hino et al. 2002). The E-Z Reader model posits two major stages of lexical processing during sentence reading. The first stage is L_1, which is also known as a familiarity check. Upon completion of L_1 the word n is sufficiently identified and signals the oculomotor system to program a saccade to word $n + 1$. The second stage is L_2, which reflects the point in lexical processing at which the word n has been sufficiently identified so that it can be integrated into the sentence and/or discourse structure. Completion of L_2 results in the shift of attention from word n to word $n + 1$. According to the model, if the integration of word n is not complete by the time that the meaning of word $n + 1$ is complete (and therefore ready to be integrated into the sentence), the flow of reading may be interrupted and the result could be redirection of attention and the eyes to word n or slowed processing of word $n + 1$ (Pollatsek et al. 2008). Integration difficulties can occur fairly rapidly and can influence gaze duration on a word by influencing the probability of making a refixation on the word (Reichle et al. 2009).

According to the feedback activation framework it is assumed that a task like sentence processing, which relies on meaning information, is based primarily on activation in semantic units. It is also assumed that words that evoke richer semantic representations, such as words that have high BOI ratings, result in faster semantic settling. The interpretation of our results that can be derived from this view is that faster semantic settling resulted in faster integration of the high BOI words into the sentence frames. Within the E-Z Reader model faster integration could be afforded by this faster semantic settling and would result in faster processing in L_2 and a reduced probability that the integration of word n would be incomplete by the time that word $n + 1$ was identified and ready to be integrated into the sentence. The avoidance of this integration conflict could, in turn, explain our observation of fewer regressions to and shorter total fixation durations on the high BOI words.

4. Conclusions

The novel finding in the present study was the presence of a facilitatory BOI effect in a sentence reading task, where the behaviors of interest are non-manual responses and are therefore unlikely to be simply the result of task-specific motor system priming. In addition, whereas in previous research BOI effects have been studied using tasks involving a decision component in which participants respond to single words, the present findings show that BOI effects are also present in a situation that taps normal reading, when words are read in context. Our results are therefore consistent with the idea that prior bodily experience influences off-line cognition, in particular, incidental language processing, and that sensorimotor knowledge is relevant to lexical semantics.

Appendix

Target words appear in brackets in the following order: low BOI, high BOI.

1. Jennifer was surprised that the [knight, priest] spoke eloquently.
2. Ava could not believe that Sam was excited about the [hog, ham] on his back porch.
3. Alexander secretly thought that his [gang, mate] was behaving strangely.
4. Levi thought that Zane would see the [witch, sword] on the stage.
5. Around the next bend and beyond the [lane, gate] was a small lake.
6. Judith saw the reflection of the [sun, cat] in the oval mirror.
7. Bob was offended so he threw the [case, belt] across the room.
8. Jeremiah and Duncan watched the [herd, goat] eat the grass in the field.
9. The British museum preserved pictures of the [coast, wheel] for future generations.
10. Tom realized that he had left the [brain, drill] on the bench.
11. Jessica followed the instructions as she spread the [tar, mat] on the garage floor.
12. Sophie purposefully overlooked the [lint, silk] on the sweater.
13. Angela cried because Eric had stolen her [heart, child] in the night.
14. Billy had agreed to take the [loot, cart] to a secret location.
15. Clinton was surprised to see the [frost, purse] on the lawn.
16. Caroline was concerned when she saw that the [well, seat] was beginning to crack.
17. Daniel deliberately tossed the [ash, toy] in the dumpster.

18. Charlotte and Helen spotted the [seal, cord] in the water.
19. The sheep found the novelty of the [place, thing] to be too stimulating.
20. Lindsay and Kevin thought that the [zoo, pie] was overrated.
21. Patrick was surprised that a [flea, fish] could jump so high.
22. Marissa had decided to use the [stripe, string] as a design element.
23. Graham was going to be in the [jail, cage] until daybreak.
24. Don't tell anyone that we left the [pit, pet] in the garden.
25. Jasmine carefully placed the jewels in his [tomb, palm] before leaving.
26. I drew a simplistic sketch of the [bay, hat] on the napkin.
27. Kaylee and Nicole were worried that the [hall, food] wouldn't be ready on time.
28. Heather examined her patient's [back, neck] during the appointment.
29. Zoie was forced to use stain remover on the [spot, suit] yesterday.
30. Jacob often wondered if his [tail, mole] was normal.
31. The short stick would not enter the [slit, lock] in the wall.
32. Stephanie quickly returned the [game, gift] to the department store.
33. Frank was confident that he had left the [pint, card] on the table.
34. Cassidy felt the chill from the [fog, ice] through his jacket.
35. Olivia and Brandon stood on their [roof, feet] to view the scene.
36. Sebastian looked under the truck and saw that a [band, hook] had to be replaced.
37. You are foolish to believe that a [seam, nail] will repair the damage.
38. Franklin was pleased that he bought the [spade, pearl] at a garage sale.
39. Please don't lie to Anne about why the [star, bowl] could not be found.
40. Michael realized that the [lung, tube] was punctured beyond repair.

References

Balota, D. A., M. J. Yap, M. J. Cortese, K. I. Hutchinson, B. Kessler, B. Loftis, J. H. Neely, D. L. Nelson, G. B. Simpson & R. Treiman. 2007. The English lexicon project. *Behavior Research Methods* 39. 445–459.

Barsalou, L. W. 1999. Perceptual symbol systems. *Behavioral and Brain Sciences* 22. 577–660.

Barsalou, L. W. 2003a. Abstraction in perceptual symbol systems. *Philosophical Transactions of the Royal Society of London: Biological Sciences* 358. 1177–1187.

Barsalou, L. W. 2003b. Situated simulation in the human conceptual system. *Language and Cognitive Processes* 18. 513–562.

Barsalou, L. W., K. Simmons, A. K. Barbey & C. D. Wilson. 2003. Grounding conceptual knowledge in modality-specific systems. *Trends in Cognitive Sciences* 7. 84–91.

Clark, A. 1997. *Being there: Putting brain, body, and the world together again*. Cambridge, MA: MIT Press.

Davis, C. J. 2005. N-Watch: A program for deriving neighborhood size and other pshycolinguistic statistics. *Behavior Research Methods* 37. 65–70.

Gibbs, R. W. 2006. *Embodiment and cognitive science*. New York: Cambridge University Press.

Glenberg, A. M. & M. P. Kaschak. 2002. Grounding language in action. *Psychonomic Bulletin and Review* 9. 558–565.

Helbig, H. B., M. Graf & M. Kiefer. 2006. The role of action representations in visual object recognition. *Experimental Brain Research* 174. 221–228.

Helbig, H. B., J. Steinwender, M. Graf & M. Kiefer. 2010. Action observation can prime visual object recognition. *Experimental Brain Research* 200. 251–258.

Hino, Y. & S. J. Lupker. 1996. Effects of polysemy in lexical decision and naming: An alternative to lexical access accounts. *Journal of Experimental Psychology: Human Perception and Performance* 22. 1331–1356.

Hino, Y., S. J. Lupker & P. M. Pexman. 2002. Ambiguity and synonymy effects in lexical decision, naming, and semantic categorization tasks: Interactions between orthography, phonology, and semantics. *Journal of Experimental Psychology: Learning, Memory and Cognition* 28. 686–713.

Hoenig, K., C. Muller, B. Herrnberger, E.-J. Sim, M. Spitzer, G. Ehret & M. Kiefer. 2011. Neuroplasticity of semantic representations for musical instruments in professional musicians. *NeuroImage* 56. 1714–1725.

Juhasz, B. J. & K. Rayner. 2003. Investigating the effects of a set of intercorrelated variables on eye fixation durations in reading. *Journal of Experimental Psychology: Learning, Memory and Cognition* 29. 1312–1318.

Kiefer, M. & F. Pulvermüller. In press. Conceptual representations in mind and brain: Theoretical developments, current evidence and future directions. *Cortex*.

Kiefer, M., E.-J. Sim, H. B. Helbig & M. Graf. 2011. Tracking the time course of action priming on object recognition: Evidence for fast and slow influences of action on perception. *Journal of Cognitive Neuroscience* 23. 1864–1874.

Kiefer, M., E.-J. Sim, S. Liebich, O. Hauk & J. Tanaka. 2007. Experience-dependent plasticity of conceptual representations in human sensory-motor areas. *Journal of Cognitive Neuroscience* 19. 525–542.

Kucera, H. & W. Francis. 1967. *Computational analysis of present-day American English*. Providence, RI: Brown University Press.

Lakoff, G. & M. Johnson. 1999. *Philosophy in the flesh: The embodied mind and its challenge to western thought*. New York: Basic Books.

Myung, J., S. E. Blumstein & J. C. Sedivy. 2006. Playing on the typewriter, typing on the piano: Manipulation knowledge of objects. *Cognition* 98. 223–243.

Pecher, D. & R. A. Zwaan. 2005. Introduction to grounding cognition. In D. Pecher & R. A. Zwaan (eds.), *Grounding cognition: The role of perception and action in memory, language and thinking*, 1–7. Cambridge: Cambridge University Press.

Pexman, P. M., I. S. Hargreaves, P. D. Siakaluk, G. E. Bodner & J. Pope. 2008. There are many ways to be rich: Effects of three measures of semantic richness on visual word recognition. *Psychonomic Bulletin and Review* 15. 161–167.

Pollatsek, A., B. J. Juhasz, E. D. Reichle, D. Machacek & K. Rayner. 2008. Immediate and delayed effects of word frequency and word length on eye movements in reading: A reversed delayed effect of word length. *Journal of Experimental Psychology: Human Perception and Performance* 34. 726–750.

Pollatsek, A., M. Perea & K. Binder. 1999. The effects of "neighborhood size" in reading and lexical decision. *Journal of Experimental Psychology: Human Perception and Performance* 25. 1142–1158.

Pollatsek, A., E. D. Reichle & K. Rayner. 2006. Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology* 52. 1–56.

Pylyshyn, Z. 1984. *Computation and cognition: Towards a foundation for cognitive science*. Cambridge, MA: MIT Press.

Rayner, K. 1998. Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin* 124. 371–422.

Reichle, E. D., T. Warren & K. McConnell. 2009. Using E-Z Reader to model the effects of higher level language processing on eye movements during reading. *Psychonomic Bulletin and Review* 16. 1–21.

Siakaluk, P. D., P. M. Pexman, L. Aguilera, W. J. Owen & C. R. Sears. 2008. Evidence for the activation of sensorimotor information during visual word recognition: The body-object interaction effect. *Cognition* 106. 433–443.

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

Tillotson, S. M., P. D. Siakaluk & P. M. Pexman. 2008. Body-object interaction ratings for 1,618 monosyllabic nouns. *Behavior Research Methods* 40. 1075–1078.

Weisberg, J., M. van Turennout & A. Martin. 2007. A neural system for learning about object function. *Cerebral Cortex* 17. 513–521.

Wellsby, M., P. D. Siakaluk, W. J. Owen & P. M. Pexman. 2011. Embodied semantic processing: The body-object interaction effect in a non-manual task. *Language and Cognition* 3. 1–14.

Wilson, M. 1988. The MRC psycholinguistic database: Machine readable dictionary, Version 2. *Behavioural Research Methods, Instruments and Computers* 20. 6–11.

Wilson, M. 2002. Six views of embodied cognition. *Psychonomic Bulletin and Review* 9. 625–636.

Yap, M. J., S. E. Tan, P. M. Pexman & I. S. Hargreaves. 2011. Is more always better? Effects of semantic richness on lexical decision, speeded pronunciation, and semantic classification. *Psychonomic Bulletin and Review* 18. 742–750.

Zeno, S. M., S. H. Ivens, R. T. Millard & R. Duvvuri. 1995. *The* educator's *word frequency guide*. United States of America: Touchstone Applied Science Associates, Inc.