The neglected role of lexical ambiguity in embodied cognition models

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Abstract

We focus on lexical ambiguity to convene two frameworks – embodied cognition and models of representation of ambiguous words. By harnessing the well-established findings from the two approaches, we achieve novel insights of interest for both fields. In the first of the four studies, we collected sensorimotor ratings for separate meanings/senses of ambiguous words and compared homonyms (words with multiple unrelated meanings; e.g. *bank*) and polysemes (words with multiple related senses; e.g. *paper*) for the similarity of the obtained profiles on the 12 scales to demonstrate that the linguistic categorization was mirrored in the sensorimotor experience with the referents. We then collected subjective ratings of semantic similarities between pairs of meanings/senses within a word and investigated their relation with the similarity of the sensorimotor profiles to corroborate that the sensorimotor-based similarity was semantic in nature. Finally, we tested if the obtained measures were predictive of processing. Although the visual lexical decision task failed to provoke deep enough processing, our novel paradigm of continuous priming in the experience verification task revealed that preactivation of the sensory modality that is shared between two senses of a polysemous word enhanced facilitation by the related prime. Our results speak in favour of sensorimotor information as a component of partially overlapping representations of polysemous senses and advise future norming studies to take into account lexical ambiguity.

Keywords

embodied cognition; experience verification task; lexical ambiguity; lexical decision task; priming; sensorimotor experience; sensorimotor ratings

Introduction

Processing and representation of word meaning (and conceptual knowledge in general) have been addressed from numerous perspectives (e.g. see Kumar, 2021 for a detailed review of semantic memory). However, different approaches sometimes focus on different phenomena, thus leaving the important empirical effects nested within a single framework and preventing important insights they could provide regarding the debates within other approaches. Here, we focus on two frameworks – embodied cognition (Barsalou, 2008) and lexical ambiguity models (Rodd, 2018) to address the nature of the representation of ambiguous words. On the one hand, we bring to focus the common practice of collecting lexical-semantic norms at the level of the word as a unit of meaning and apply the same procedure separately for individual meanings/senses of ambiguous words. On the other hand, we investigate the potential of sensorimotor information as a gateway to testing models of representation of ambiguous words.

Word meaning representation within the embodied cognition framework

The growing body of recent empirical evidence suggests that features originating from sensory and motor experiences with the world around us are crucial for semantic representation of concepts, which is contrary to the traditional conception, which describes the conceptual knowledge coded in language as the amodal system nested between inputs from perception and outputs to motor system (Chatterje, 2010; Fodor, 1975; Mahon & Caramazza, 2005; Pylyshyn, 1984). Building on the dual coding theory, which postulated analogous and amodal representations in parallel (Paivio, 1971; 1986; 1991; but see also Kaup et al., 2024), contemporary theories operating under the name *embodied cognition* further elaborated the importance of previous sensorimotor (SM) experience for representation. Although heterogeneous in the type and importance of the postulated role of sensorimotor information, all of them agree that the semantic representation is at least partially composed of interconnected, modally specific sensorimotor representations that originate from the previous SM experience with the entity labeled by the word (for review see Meteyard et al., 2012).

According to some models of embodied cognition (Barsalou, 1999; 2008; 2010), reading or hearing a word (e.g., *apple*) leads to a simulation of previous actual sensory and motor experience with an object denoted by that word (e.g. information about the appearance of an apple, its texture, the way the apple is held in the hand, etc.) Theories of strong embodiment, which take the most extreme view, even suggest that sensory and motor neurons activated during word comprehension are the same ones that were active during sensorimotor experience with an object. There is a growing body of electrophysiological and neuroimaging evidence showing that processing of the verbal material referring to sensorimotor concepts is coupled with higher activation in sensorimotor cortical areas. It was shown that processing of verbs referring to motor actions resulted in activation of the corresponding cortical areas responsible for planning, organising, and executing motor actions specific for the effector that verbs denote (hand, foot, head, etc.; Pulvermüller et al., 2000; 2001). This finding was replicated many times on both verbs (Aziz-Zadeh et al., 2006; Hauk & Pulvermüller, 2004; Hauk et al., 2004) and nouns referring to specific sensory features (e.g. Chao et al., 1999; Gonzáles et al., 2006; Kiefer et al., 2008; del Prado Martin et al., 2006; Pulvermüller & Hauk, 2006; Simmons et al., 2007). More evidence comes from studies showing that lesions affecting sensory processing or motor actions result in problems with processing of corresponding verbal material (Bak et al., 2001; Boulenger et al., 2008; Buxbaum & Saffran, 2002; Fernandino et al., 2013a; 2013b; Trumpp et al., 2013).

To assess the typical sensorimotor experience associated with word stimuli, norming studies were conducted where participants rated the extent to which it was possible to experience something by seeing/hearing/touching, etc. (Chen et al., 2019; Filipović Đurđević et al., 2016; Lynott & Connell, 2009; 2013; Lynott et al., 2019; Miklashevsky, 2018; Popović Stijačić, 2021; Repetto et al., 2023; Speed & Majid, 2017; Vergallito et al., 2020; Zhon et al., 2022). Validation of the norms was achieved from two directions. On the one hand, the validity of the norms was confirmed by showing that sensorimotor information indeed did reflect semantic information. Namely, recent studies (Speed & Majid, 2017; Wingfield & Connell, 2023) demonstrated that similarity between the profiles of sensorimotor ratings correlated positively with rated semantic similarity between the two words, thus indicating that sensorimotor information was semantic in nature, as claimed by theories of embodiment. On the other hand, multiple experiments demonstrated that sensorimotor information associated with the word was predictive of cognitive processing. For example, the modality-specific perceptual strength, i.e. an average rating of individual sensory experience (*visual strength, auditory strength,* etc.), is shown to be predictive for reaction latencies in the lexical decision task (Connell & Lynnott, 2009; Filipović Đurđević et al., 2016; Lynott & Connell, 2013; Popović Stijačić, 2021). The integrative measures (measures derived from modality-specific ratings) also corroborated the importance of the sensorimotor information, although yielding inconsistent results concerning the best candidate for the single quantification of the overall perceptual richness. Some studies revealed the advantage of maximal sensory strength (highest per-modality rating; Lynott & Connell, 2013), whereas others reported vector length (Eucledean distance, Minkowski distance; Filipović Đurđević et al., 2016; Lynott et al., 2019), sensory entropy (the imbalance among the sensory ratings; Filipović Đurđević et al., 2016), summed perceptive strength (sum of per-modality ratings; Speed & Majid, 2017), and modality exclusivity (standing-out of the one sensory modality among the others; Lynott & Connell, 2009; Popović Stijačić, 2021) as the best candidates. The effects of perceptual richness were also shown to affect memory (Popović Stijačić & Filipović Đurđević, 2015; 2022) and even the performance of individuals with Mild Cognitive Impairment and First Episode Psychosis (Filipović Đurđević et al., 2024a; Filipović Đurđević et al., 2024b). However, although numerous norming studies have been conducted so far, they have focused on a word as a unit, thus neglecting the phenomenon of lexical ambiguity.

Representation and processing of lexical ambiguity

In language, it often happens that one word can be interpreted in more than one way (Brochhagen et al., 2023; Piantadosi et al., 2012; Xu et al., 2020). It is estimated that over 80% of words are ambiguous (Rodd et al., 2002). If a word has two or more completely unrelated meanings that, by accident, share the same word form (e.g. *bark* – loud noise or part of the tree), we call them homonyms (word forms that map onto multiple *meanings*). If a word has two or more related, semantically similar referents (e.g. *head – a* body part or a leading person), we refer to them as polysemes – word forms that map onto multiple *senses*. Multiple studies demostrated that, in comparisson to unambiguous words, polysemes elicited shorter reaction latencies whereas homonyms elicited longer reaction latencies in shallow processing and that an increase in the number of meanings/senses enhanced this effect (e.g. lexical decision task, or naming; Armstrong & Plaut, 2008; 2011; Beretta et al., 2005; Klepousniotou & Baum, 2007; Rodd et al., 2002; in Serbian: Filipović Đurđević, 2019; Filipović Đurđević & Kostić, 2008; 2009; Mišić & Filipović Đurđević, 2022a; 2022b). The processing differences between polysemy and homonymy is so far best explained by the Parallel distributed processing (PDP) models (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004; but see also Frisson, 2009, or Klein & Murphy, 2002 for different accounts). They postulate that the mental representation is distributed in the pattern of activation of basic units that represent different semantic features. Because different polysemous senses share features, they have overlapping basic units activation patterns, which gives them a processing advantage. When a polysemous word is presented without a context, the blend of all senses activates, which leads to a facilitatory effect and faster recognition of polysemous words, compared to homonyms and their non-overlapping representations that mutually inhibit each other. Additional support comes from studies that have taken into account the difference in the degree of polysemous sense relatedness: they showed that the more similar the word senses are, the bigger the postulated overlapping area between their activation patterns, which would lead to a bigger facilitatory effect in lexical decision task (Armstrong & Plaut, 2008; 2011; Beretta et al., 2005; Klepousniotou & Baum, 2007; Rodd et al., 2002). This pattern is also recorded using the priming paradigm, with two polysemous senses of the same word being prime and target stimuli. The facilitatory effect of one sense's processing on another sense's processing was stronger when senses were more similar (Brown, 2008; Klepousniotou et al., 2008; but see Eddington & Tokowicz, 2015 for a comprehensive review).

Knowledge gap and study goals

Although prevalent in language and relevant for cognitive processing, the phenomenon of lexical ambiguity has so far been neglected by the widespread approach of collecting sensorimotor ratings within the embodied cognition framework. By far, many studies collected extensive sensorimotor norms (Chen et al., 2019; Filipović Đurđević et al., 2016; Lynott & Connell, 2009; 2013; Lynott et al., 2019; Miklashevsky, 2018; Popović Stijačić, 2021; Repetto et al., 2023; Speed & Majid, 2017; Vergallito et al., 2020; Zhon et al., 2022) and showed that norm-based measures are predictive for words processing (Filipović Đurđević et al., 2016; Lynott & Connell, 2013; Popović Stijačić, 2021; Speed & Majid, 2017), which is in line with embodied cognition models (Barsalou, 1999; 2008; 2010; Meteyard et al., 2012). However, neither empirical studies nor models of embodied cognition have yet taken into account that the vast majority of all words are ambiguous. With that in mind, the justification of the previous norming practice can be questioned, due to the uncertain nature of measures obtained in this way. Namely, we can not be certain of the exact meaning that a participant holds in mind while rating, e.g. to what extent one can taste *a bar*, when rating would be different in the case of *an iron bar, a chocolate bar and a local bar* (as also suggested by Myachykov & Fischer, 2019; Myachykov et al., 2014).

To the best of our knowledge, there have only been two attempts to collect such data, and both pointed towards the importance of considering sensorimotor experience with individual senses/meanings of the ambiguous words. Filipović Đurđević and Kostić (2017) collected concreteness ratings for 150 polysemous Serbian words (following the typical approach in the field; e.g. Altarriba et al., 1999; Brysbaert et al., 2014a; 2014b), but for the same words, they also collected concreteness ratings for the individual senses. Their results revealed moderate positive correlation between the concreteness ratings of the word and the averaged concreteness ratings of individual senses (r~.60). The correlation coefficient was driven by the correlation with the concreteness rating of the dominant sense (r~.70), whereas the correlation with the average concreteness of the subordinate senses was lower (r~.20, or null). Their findings suggested that the participants mostly relied on the dominant sense when rating the word concreteness of the polyseme. However, they also suggested that word concreteness could not be reduced to the concreteness of the dominant sense, i.e. that the semantic uncertainty caused by the lexical ambiguity affected the word rating. More recently, in an unpublished manuscript, Trott & Bergen (2022) collected sensorimotor ratings for 117 words from the Lancaster Sensorimotor Norms (Lynott et al., 2019) and also observed only partial overlap. These early attempts strongly suggested that lexical ambiguity should be taken into account when discussing the influence of sensorimotor experience on the form-to-meaning mapping.

Models of lexical ambiguity have so far focused on the question of the relationship of separate senses/meanings, as well as the dynamics of the disambiguation process (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004), whereas the *epistemic aspect* of hypothesized basic units has been neglected. Although there is a growing amount of research that stresses the importance of sensorimotor experiences for representation of knowledge, and the models of lexical ambiguity do not exclude their relevance, never before have sensorimotor features been considered as candidates for basic units in coding the meaning of ambiguous words (i.e. representation of senses/meanings).

For that reason, the main goal of this study is to investigate the role of sensorimotor information in the representation and processing of ambiguous words. We pursue this goal in steps. First, we investigate if the linguistic difference between polysemy and homonymy is reflected in the sensorimotor profiles of their meanings/senses (Study 1a) and if the sensorimotor information obtained for senses/meanings is related to semantics (Study 1b). Second, we investigate if sensorimotor information is related to the processing of polysemous words in a semantically shallow task of word recognition (Study 2a) and semantically deeper processing (Study 2b).

Study 1a: Collecting and evaluating sensorimotor ratings for meanings/senses

In Study 1a, we collected ambiguity-sensitive sensorimotor norms, i.e. we collected ratings on sensorimotor scales for specific meanings and senses of ambiguous words, rather than for words presented in isolation (without disambiguating context). We did so for the range of sensorimotor scales reported in Lynnott and colleagues (2019), with one modification. Namely, the dimension of motor experience using the head was separated into two distinct scales: using head as physical body part in interacting with objects and using head as mental structure in thinking about objects/ideas (this modification had also been suggested in the Lancaster Sensorimotor Norms paper to resolve the confound observed in their study).

To check if the nuance of collecting per-sense/per-meaning ratings is relevant, i.e. rooted in the linguistic distinction of homonymy and polysemy, in Study 1a, we focused on sensorimotor profiles of separate meanings/senses. More precisely, we looked into the relation among sensorimotor profiles of different meanings/senses within a word. We derived our prediction by crossing the linguistic qualification of homonymy and polysemy (unrelatedness of homonymous meanings vs. relatedness of polysemous senses) and the psychological qualification of sensorimotor information as the component of meaning representation. Based on that, we expected the sensorimotor profiles to be more similar for the senses within a polysemous word than for the meanings within a homonymous word. Moreover, we also tested whether homonymy/polysemy status could be predicted based on the similarity of the sensorimotor profiles of meanings/senses within a word.

Data availability

The list of experimental materials along with trial-level data and analysis code (for all of the studies we report in this paper) is available on OSF repositorium: https://osf.io/jwrny/?view_only=d6f0dcb238db4c229de9a5561443829a

Method

Participants

The initial pool consisted of 91 participants that were first-year psychology students from the University of Belgrade, who participated as a part of the activities for course credits. They signed the informed consent form approved by the Institutional Review Board of Department of Psychology at the Faculty of Philosophy, University of Belgrade (Protocol #2021-66).

Materials and design

Staring from the previous databases in Serbian (Filipović Đurđević, 2019; Filipović Đurđević & Kostić, 2017; Mišić et al., 2024; Popović Stijačić, 2021), we selected 98 ambiguous nouns of the Serbian language: 34 homonyms and 64 polysemes. The polysemous words were chosen in such a way that among their senses there were those created by metaphor and those created by metonymy to ensure the existence of variability in terms of similarity of meaning, i.e. covering the entire postulated continuum of ambiguity (Klepousniotou & Baum, 2007). Although the selected words had a range of 2-19 meanings/senses, to control for the number of presentations in our study, for each word we selected 2-4 meanings/senses, which resulted in a total of 280 meanings/senses. The stimuli consisted of the references to individual meanings/senses of these words, either by placing a noun in a syntagm (e.g. *table [for eating])* or by using a short description (e.g. *key [button on a keyboard]*). In the next step, for each word, we created pairs of referents (N = 282), making all possible combinations of the preselected meanings/senses for the word in question (e.g. *key [on a keyboard] and key [for a door]*). The pair was classified as homonymous if the two referents were listed as separate dictionary entries and as polysemous if they were listed within a single entry (Filipović Đurđević, 2019; Filipović Đurđević & Kostić, 2008; 2017; 2021; Rodd et al., 2002). Out of 282 referent pairs, 61 (21.631%) were classified as pairs of homonymous meanings and 221 (78.369%) were classified as pairs of polysemous senses. Classification can be seen in Supplementary Material 1.

Additionally, to ensure the calibration of participants to the whole range of sensorimotor scales, we selected verb + noun phrases (e.g. *to taste an apple*) from the Lancaster Sensorimotor Norms (Lynott et al, 2019), in a way that for each of the 12 sensorimotor scales, we selected two stimuli on both of the positive and negative extremes and one with a moderate rating, resulting in a total of 36 phrases.

Procedure

Sensorimotor norms were collected by using the SoSci software (Leiner, 2019; the SoSci project is available in Supplementary Material 2).

Participants were instructed to use a five-point Likert scale to express to what extent some concept could be experienced on 12 sensory and motor scales, adapted from Lynott and colleagues (2019). Six scales were related to sensory experience: to experience something 1. by seeing, 2. by hearing, 3. by touching, 4. by smelling, 5. by tasting and 6. by interoception (senses inside the body). The other five scales were related to motor actions: by performing an action 1. by hand/arm, 2. by foot/leg, 3. by torso, 4. by head and 5. by mouth/throat. The twelfth scale referred to performing actions by head in the metaphorical sense (i.e. thinking). The distinction was clarified in the instructions (e.g. using a head to handle a ball vs. using a head to handle ideas). Because using the head to handle ideas does not reflect a motor action (and we are testing the sensorimotor representations), analyses were conducted both including and omitting this scale.

Stimuli for calibration were presented before the main part and all of the participants rated the same 36 phrases in randomized order prior to the main part. In the main part, participants rated 57 randomly chosen stimuli on all 12 scales. Stimuli order was randomised, but the order of scales was fixed to avoid additional attention load. The whole procedure lasted about 30 minutes.

Results & Discussion

Descriptive statistics, t-tests and correlation analysis were conducted in JASP 0.17.2.1 (JASP Team, 2023), canonical discriminant analysis was conducted in IBM SPSS Statistics 23 (IBM Corp., 2015), and all of the graphs were created in R, using packages ggplot2 (Wickham, 2016) and ggpubr (Kassambara, 2023).

In the preprocessing phase, from the initial pool of 91 participants, we filtered out those with a too short instructions reading time and a too large percentage of “I don’t know the meaning” answers. The final pool consisted of 77 participants. Each of the initial 280 stimuli (meanings/senses) was rated 16 times on average, and from the initial pool, we excluded 5 stimuli that were unfamiliar to participants, i.e. that didn’t have enough participants’ ratings. The database containing sensorimotor norms for 275 meanings/senses is available in Supplementary Materials 3, and the exclusion criteria are available in Supplementary Materials 4.

Descriptive statistics for 12 sensorimotor scales are presented in Table 1. A sensory modality that emerged as the most dominant for this stimulus sample was vision, followed by touch, whereas interoception and taste had the smallest average score. This is in line with previous studies (Filipović Đurđević et al., 2016; Lynott et al., 2019; Popović Stijačić, 2021), which suggested that our stimulus sample was representative. The most dominant effector scale was hand/arm, and the least dominant were mouth/throat, torso and head (as part of the body). This pattern deviated from findings in the previous study (Lynott et al., 2019), where the head scale was the most dominant, followed by the hand/arm. However, we beleive that this accumulation of higher scores in the case of the head was a consequence of the confound between two interpretations of the original scale, that were separated in our study. It was shown that the average estimates for the head as a moving part of the body and the head as a brain differed ($U=68540.5$, $p<.001$), which pointed towards the justification of separating these two measures.

Table 1.

Descriptive statistics for sensorimotor norms.

SM modality	*Min*	*Max*	*Mdn*	*M*	*SD*	*Skewness*	*Kurtosis*
seeing	1	5	4.875	4.482	.956	-2.269	4.067
touching	1	5	4.588	3.949	1.253	-1.198	-.053
hearing	1	5	2.154	2.514	1.246	.740	-.764
smelling	1	5	2.067	2.408	1.160	.879	-.340
tasting	1	5	1.632	1.970	1.065	1.812	2.452
interoception	1	4.667	1.667	1.925	.808	1.239	.961
hand/arm	1	5	4.308	3.725	1.308	-.835	-.762
head (brain)	1.273	4.813	2.500	2.692	.792	.769	-.124
head (body)	1	3.563	1.556	1.616	.445	1.259	2.517
foot/arm	1	4.8	2.471	2.474	.879	.250	-.552
mouth/throat	1	5	1.588	1.904	.971	1.915	3.028
torso	1	3.438	1.615	1.655	.452	1.017	1.649

Using the collected sensorimotor ratings, we calculated pairwise sensorimotor similarity between meanings/senses within a word (N = 282) by using the Pearson correlation (see Table 2 for illustration). The average correlation of sensorimotor similarity calculated on 11 motor scales was .617, ranging from -.549 to .991, but the distribution of the SM similarity measure was skewed. With Skewness being -1.114, the great majority of the referent pairs were estimated to be very similar in the sensorimotor way.

Table 2.

Schematic illustration of calculating sensorimotor similarity of meaning/sense referents pair, based on sensorimotor norms for the individual meaning/sense of an ambiguous word.

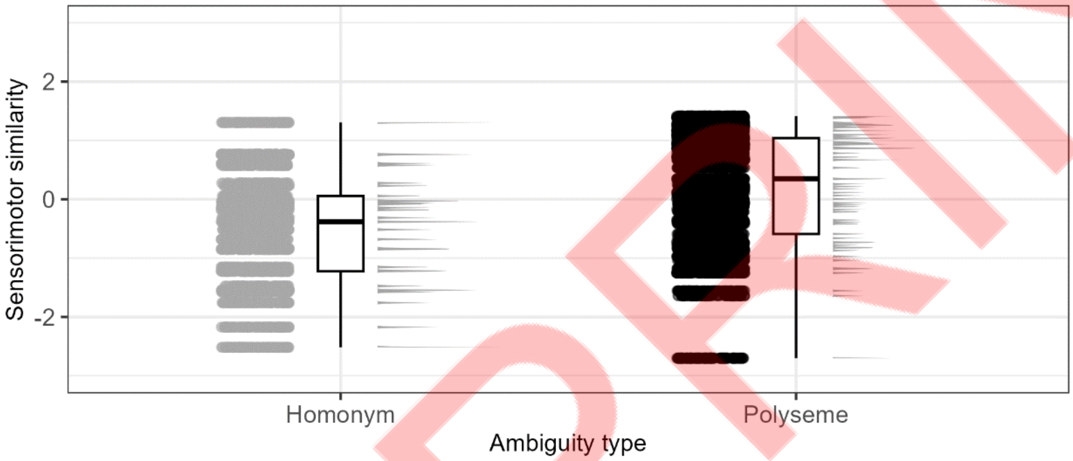
	to see	*to hear*	*to smell*	*to touch*	*to taste*	*intero-ception*	*by hand or arm*	*by foot or leg*	*by torso*	*by head*	*by mouth or throat*
key (keyboard)	5	4.2	1	5	1	1	5	1.1	1	1	1
key (door)	5	2.1	1.5	5	1.2	1	5	1	1	1	1.3

Pearson's correlation (key1,key2) would here be: $r(9) = .935$, $t = 7.91$, $p < .001$

Because of the non-normal distribution of the similarity measure, we used the Mann-Whitney test to examine the difference between the homonymic and polysemous pairs regarding their sensorimotor similarity. As expected, the sensorimotor profiles of polysemous pairs were more similar on average (Mdn = 0.823) than the sensorimotor profiles of homonimic pairs (Mdn = 0.492), and the observed difference was significant (U=3804, Z=-5.208, p<.001; see Figure 1; Supplementary Materials 5 & 6).

Figure 1.

The distribution of ratings of sensorimotor similarity for homonyms and polysemous nouns.



Having shown that senses/meanings that denote similar entities also have similar sensorimotor representation, we moved forward to test if the homonymy/polysemy status could be predictied by the similarity of their sensorimotor profiles, and to additionally examine the relative contribution of each of the 11 sensorimotor scales to the differentiation between homonyms and polysemous nouns. We calculated 11 separate distance measures – one for every sensorimotor scale, by subtracting the values attributed to each of the senses/meanings within a pair on the dimension (scale) in question. This way, for each noun, we had the numerical measure of the degree to which all of that word's meanings/senses differ on each of the 11 scales separately (Supplementary Material 7). Those 11 sensorimotor distance measures were our predictors in descriptive canonical discriminant analysis, and the two criterion groups were homonyms (N=33) and polysemes (N=64). We observed a statistically significant canonical correlation coefficient of .522 (χ^2(11)=28.530, p<.05), with 77.3% of words correctly classified as homonym/polysemous. Group centroid for homonyms was .844 and -.435 for polysemes, which suggested that homonyms had higher sensorimotor distances. Scales that contributed the most to the definition of canonical discriminant function were *hearing* (r=.483, β=.518) and *touching* (r=.466, β=1.128), while *seeing* was a redundant variable (r=.412, β=.026). Other variables were either bad predictors or redundant/suppressor variables, with much smaller values of coefficients of canonical discriminant structure and standardised canonical discriminant coefficients.

To conclude the findings from Study 1a, we showed that the linguistic categories of homonymy and polysemy were reflected in the sensorimotor regularities. The related, polysemous senses are shown to have more similar sensorimotor profiles, as opposed to the unrelated, homonymic meanings, shown to have less similar sensorimotor profiles. We also showed that the group membership (polysemy/homonymy) can be predicted based on the similarity of the ratings of auditory and tactile experience with the entities denoted by their meanings/senses. The uninformativeness of the usually dominant *seeing* scale is possibly a consequence of a high correlation between the similarity of *touching* and *seeing* (r = .693, p<.001), with the *touching* being more discriminative. Given the novel and exploratory nature of this analysis, it is worth of attention that the same two senses (touching and hearing) were found to differ the most between concrete and abstract concepts (Banks & Connell, 2023), along with interoception.

Study 1b: Collecting and evaluating semantic similarity ratings for meanings/senses

In Study 1b, we collected subjective semantic similarity ratings for the pairs of meanings/senses within words. Because Study 1a demonstrated that categorical linguistic distinction between homonymy and polysemy was reflected in the sensorimotor profiles of their meanings/senses, in Study 1b, we took the next step of validating this finding in the psychological context of subjectively perceived similarity, as operationalised by semantic similarity ratings. We first compared homonymy and polysemy for the average semantic similarity ratings, to confirm for our set of words that the linguistic distinction is reflected in the psychological realm of subjective semantic similarity. Then, we looked into the relationship between the similarity of the profiles of sensorimotor ratings (as calculated in Study 1a) and the rated semantic similarity of the meaning/sense pairs within a word (collected in this study). We predicted a positive correlation between them. This finding would include the distinction between homonymy and polysemy observed in Study 1a, but would also capture a more fine-grained differentiation in the overlap of meanings/senses (continuum of ambiguity; Klepousniotou, 2002; Klepousniotou et al., 2008; Yurchenko et al., 2020).

Method

Participants

As in Study 1a, participants were first-year psychology students from the University of Belgrade, whose participation was acknowledged as course credits. The initial pool consisted of 90 participants who signed the informed consent form approved by the Institutional Review Board of the Department of Psychology (Protocol #2021-66). The participants were sampled from the same pool of first-year psychology students as the participants from Study 1a. However, the overlap was only partial, as the stimuli were drawn from a bigger pool randomly for each participant. Additionally, the two research phases were 2 weeks apart, and they were presented as two unrelated studies to prevent the first phase from affecting the second one.

Stimuli

We presented the same stimuli that were described in Study 1a: 282 meaning/sense pairs. Additionally, to ensure the calibration of participants to the whole range of the semantic similarity scale, we selected 23 word pairs (without disambiguating context; e.g. *a mouse – a rat*) from the previous study that also collected similarity ratings (the SimLex-999 database, Hill et al., 2015), in a way that covered the entire continuum of semantic similarity. In addition, another nine pairs of meanings/senses (e.g. *work [activity, labour] – work [task]*) were selected from the database of Serbian ambiguous nouns (Filipović Đurđević & Kostić, 2017, coded for metonymy/metaphor in Manojlović & Filipović Đurđević, 2025), so that they cover the entire semantic similarity continuum.

Procedure

Using the SoSci software (Leiner, 2019; SoSci project available in Supplementary Materials 8), participants used a five-point Likert scale to rate to what extent two concepts were semantically similar (e.g. *pen [for writing]* and *pen [for sheep]*). Each pair was shown in two orders, i.e. the position of the sense during presentation was counterbalanced. Each participant rated 90 randomly chosen meaning/sense pairs. The instructions that clarified the concept of semantic similarity were adapted from Hill and colleagues (2015), focusing on the synonyms as the extreme example and pointing out the difference between semantic and associative similarity. The calibration stimulus pairs, both unambiguous and ambiguous ones, were presented before the main task, in randomised order for every participant. The entire procedure took about 20 minutes per participant.

Results & Discussion

Descriptive statistics, t-tests and correlation analysis were conducted in JASP 0.17.2.1 (JASP Team, 2023) and IBM SPSS Statistics 23 (IBM Corp., 2015), and all of the graphs were created in R, using packages ggplot2 (Wickham, 2016) and ggpubr (Kassambara, 2023).

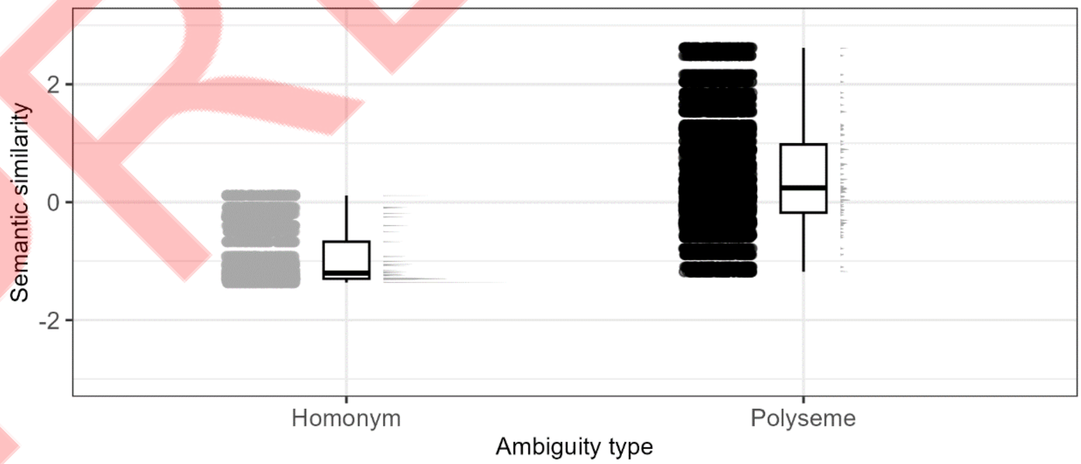
In the preprocessing phase, we excluded participants with an excessively high percentage of invalid answers and a short instruction reading time from the initial 90-participant pool, leaving 71 participants in the final pool. The exclusion criteria are available in Supplementary Material 1.

Each meaning/sense was rated 22 times on average. We observed the average semantic similarity rating of 2.078 (Sd = .897). The distribution of the semantic similarity ratings was positively skewed, with Skewness of .783 and the Shapiro-Wilk test indicating deviation from the normal distribution (W=.918, p<.001), i.e. the great majority of the referent pairs were rated as semantically dissimilar (Supplementary Materials 5 & 6).

To check if a sample of polysemous nouns and homonyms is representative, i.e. if two groups differ semantically as it would be expected from the definition of polysemy and homonymy, we first conducted a Mann-Whitney test to examine the difference between them regarding semantic similarity. On average, the polysemous pairs were found to be more semantically similar (Mdn=2.115) than homonymous pairs (Mdn=1.238; U=1161.500, Z=-9.895, p<.001; see Figure 2), which corroborated the representativeness of the sample of words in our study.

Figure 2.

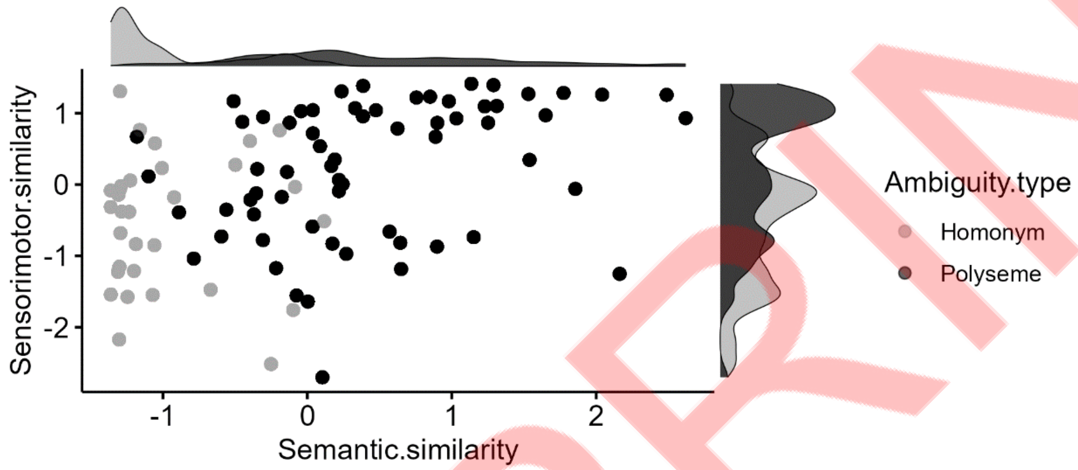
The distribution of ratings of semantic similarity for homonymous and polysemous nouns.



Next, we examined whether rated semantic similarity (a *continuous* variable) correlated with the measure of sensorimotor similarity, which was tested using Spearman's correlation (due to the observed skewness of the distributions). As predicted, it was found to be positive and significant (r_s (280)=.484, p<.001, see Figure 3 & Supplementary Material 5).

Figure 3.

The relation between semantic and sensorimotor similarity.



The observed correlation between the two similarity measures is of a similar magnitude as the one registered in the previous study (Wingfield & Connell, 2023), where it ranged from .29 to .45, depending on the database used. Although one could expect a stronger relationship with using the more precise concept definition (i.e. including the disambiguation), the results are similar. One of the reasons may lie in the observed asymmetrical distribution, i.e. accumulation of low values of semantic similarity, which was unexpected, given that the majority of the pairs were composed of polysemous senses, which are by definition similar to some extent. The explanation that seems possible is that the instructions for semantic similarity ratings could have biased participants into giving lower ratings, as the concept of semantic similarity was explained through the concept of synonyms as extremely semantically similar words, as in the previous study (Hill et al., 2015). Although participants first rated stimuli for calibration, it seems that the biasing effect of instructions remained.

However, in both Studies 1a and 1b, we showed that sensorimotor similarity was reflected in semantic similarity. Sensorimotor information or sensorimotor features seem to capture some semantic regularities in a way that similar concepts we tend to experience in the similar sensory and motor way.

Study 2a

Considering that the Study 1a and 1b informed us about the role of sensorimotor information in offline representation of meaning, the goal for Studies 2a and 2b was to address the online processing of ambiguous words, i.e. to examine if sensorimotor features actually behave like semantic features during the processing.

In Study 2a, we focused on the processing of ambiguous words in isolation, without any disambiguating context, i.e. in a lexical decision task (LDT). We based our predictions on the findings that semantic similarity of word meanings/senses facilitates processing in LDT when treated categorically, by comparing the least semantically similar homonymy, more similar metaphor and the most semantically similar metonymy (Armstrong & Plaut, 2008; 2011; Beretta et al., 2005; Klepousniotou & Baum, 2007; Rodd et al., 2002). Although there are suggestions that this relationship should be tested continuously as well (Eddington & Tokowicz, 2015; Liang et al., 2024), empirical evidence is still lacking. However, based on the previous categorical patterns, we predicted the facilitatory effect of the semantic similarity on LDT latencies. Moreover, we predicted the sensorimotor similarity to have the same effect, given the postulated and expected ability of sensorimotor information to code meaning (Speed & Majid, 2017; Wingfield & Connell, 2023). Therefore, we predicted that sensorimotor similarity (high similarity of sensorimotor profiles of word senses) would facilitate lexical decision over and above the expected facilitation by the highly rated semantic similarity.

Method

Participants

We recruited a novel group of 103 first-year psychology students from the University of Belgrade. Previous experience demonstrated that 30-50 participants were needed to detect the effects of semantic predictors in correlational designs (Filipović Đurđević & Kostić, 2023; Pexman et al., 2002; 2008). However, the number of participants was selected to be as high as possible in the circumstances, to be able to reliably estimate the size of the effect. All were native speakers of Serbian, with normal or corrected-to-normal vision and no history of reading difficulties. Ethical approval was obtained from the Institutional Review Board of the Department of Psychology at the Faculty of Philosophy, University of Belgrade (Protocol #2022-65) and the signed informed consents were collected.

Stimuli

The 97 Serbian nouns used in Studies 1a and 1b were included as stimuli, shown in isolation, without a disambiguating context. Information about the word frequency was obtained from the Frequency Dictionary of Contemporary Serbian Language (Kostić, 1999), and word familiarity, concreteness, emotional valence, arousal and imageability were assessed in the norming study (Supplementary Material 9). Word length in letters was also included as a control variable. Additionally, 97 pseudowords were generated using Wuggy, a pseudoword generator (Keuleers & Brysbaert, 2010). Finally, 3 nouns and 3 pseudowords were selected to be presented in the practice session.

Procedure

Participants performed a visual lexical decision task on the desktop computer in the laboratory with the experimenter present. The experiment was conducted using OpenSesame version 3.3.14 Lentiform Loewenfeld (Mathôt et al., 2012; Supplementary Materials 10).

Although the design was fully repeated across stimuli and participants, such that each participant was presented with all of the 97 stimuli, there were three conditions regarding the homonymy/polysemy presentation order (following Mišić & Filipović Đurđević, 2022b). One group of the participants was presented with homonyms and polysemes in a single block (v1), the second group was first shown a block of homonyms and then a block of polysemes (v2), and the third group was first shown a block of polysemes and then a block of homonyms (v3). Participants were randomly assigned to one of the three groups, and within each block, the order of stimuli was randomised for every participant. After a fixation point (1000ms), stimuli appeared printed in white lowercase Roman alphabet (Droid Sans Mono, 35 pt), centred on a black background and remained on the screen until response or until timeout (1500ms). Participants were instructed to hold their index fingers on the letter C and letter M keys on the keyboard and to respond by pressing the appropriate key (C for non-word and M for word). Before the main task, the participants were presented with a practice session, and both the practice session and the main session contained feedback (*incorrect* and *too slow*). The stimuli presented in the practice session were not included in the analyses. The full session lasted for approximately 10 minutes.

Results & Discussion

The data were analysed using R statistical software (R version 4.2.2; R Core Team, 2022), using packages lme4 (Bates et al., 2015), sjPlot (Lüdecke, 2021), lmertest (Kuznetsova et al., 2017), ggplot2 (Wickham, 2016), dplyr (Wickham et al, 2023). We started by excluding two items with less than an 75% accuracy rate (all participants were above the accuracy threshold). After filtering out pseudowords, incorrect and extremely short responses (that were probably accidental key presses; <300ms) were removed, and reaction time (RT) was inversely transformed to normalise the skewed distribution (Milin & Baayen, 2010). The complete analysis is given in the Supplementary Materials 11. We first tested the representativeness of our experiment by inspecting zero-order correlation of reaction latencies with multiple control lexical-semantic variables, and observed the effects typically observed in this type of studies: word frequency (r (93) = -.336; p < .01); familiarity (r (93) = -.747; p < .01); concreteness (r (93) = -.439; p < .01); emotional valence (r (93) = -.273; p < .01), imageability (r (93) = -.552; p < .01), (r (93) = -.049; p = .641), and word length in letters (r (93) = -.119; p = .252). Zero order correlation with reaction time was significant for semantic similarity (r (93) = -.401; p < .01), but not for sensorimotor similarity (r (93) = -.100; p = .335).

In the next step, we tested whether each of the key predictors (semantic similarity and sensorimotor similarity) accounted for variance in reaction latency after taking into account the effects of the control variables. To do so, we first built the baseline model (with control predictors), and then continued by building two separate models (one for each of the two key varaibales). The additional benefit of including the key predictors was attested by comparing the model fit with the baseline model. To control for collinearity, all control variables were subjected to principal component analysis. Six principal components whose proportion of explained variance exceeded 5% were selected, and the scores of the lexical-semantic variables on the selected principal components were further used in analyses as control predictors in linear mixed effects regression (lmer4; Bates et al., 2015a). Following Gelman and Hill (2007), we standardized the values of the key continuous predictors. Model building was guided by sequential addition of fixed effects and attesting the justification of their contribution by the comparisson of model fit via Accaice Information Criterion (AIC; Akaike, 1974; Baayen et al., 2017). For each predictor, we tested for the nonlinearity and the interactions with all of the predictors already included in the model, and kept only the parameters that were justified by the data. In the baseline model, we started with includnig of the order of trial presentation, followed by the scores on principal components ordered by their contribution to the variance (pc1, pc2, etc.). The structure of the random effects was determined by starting from the most complex structure justified by the design (Bar et al., 2013), and by trimming through RePsychling procedure (Bates et al., 2015b; Matuschek et al.,

2017) until reaching the structure that allowed the model to converge withouth reaching the singular value warning. For the final models we applied the model criticism by trimming the influential data points (residuals outside of the -2.5/2.5 range of standardized values) and re-fitting the models. The structure of the observed effects was not affected in this step, and we report the re-fitted models.

After reaching the best baseline model justified by the data, we contunued following the same procedure for the two key predictors. The inclusion of linear effects did not signifficantly improve model fit for either of them (Table 4, model 1 and model 2). However, although none of the further testing was beneficial for the sensorimotor similarity, the inclusion of the nonlinear component for the semantic similarity led to significant increse in the model fit (Table 4, model 3; the coefficients from the model are presented in Table 3, left-hand column). As illustrated in Figure 4 (left-hand plot), the effect was stronger for the low values of semantic similarity and attenuated with an increase in the values of the predictor. Further inspection revealed that the nonlinearity was a consequence of the interaction between the semantic similarity and the ambiguity type (Figure 4, right-hand panel; the coefficients from the model are presented in Table 3, right-hand column). The effect of the semantic similarity was significant with homonyms (~49ms), but null for polysemses. This model was also the best-fitting of all the attested models (Table 4, model 4).

Table 3.

Coefficients obtained in the model fitted to inverse-transformed reaction latencies with semantic similarity over the baseline model (left-hand panel) and the model with the interaction between semantic similarity and ambiguity type (right-hand panel).

	model 3			**model 4**		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
Intercept	-1.64	-1.67 – -1.60	**<.001**	-1.66	-1.70 – -1.62	**<.001**
Order of trial presentation	-.01	-.02 – -.00	**.048**	-.01	-.02 – .00	.058
pc 1	-.06	-.07 – -.05	**<.001**	-.06	-.07 – -.04	**<.001**
pc 2	-.02	-.03 – -.01	**<.001**	-.02	-.03 – -.01	**<.001**
pc 3	-.03	-.04 – -.02	**<.001**	-.03	-.04 – -.02	**<.001**
pc 4	-.04	-.06 – -.03	**<.001**	-.04	-.06 – -.02	**<.001**
pc 5	.02	.00 – .04	**.048**	.02	.00 – .04	**.035**
Semantic similarity (linear)	-1.49	-3.11 – .13	.071			
Semantic similarity (quadratic)	1.55	.23 – 2.88	**.021**			
pc 1 × pc 4	.01	.00 – .02	**.007**	.01	.00 – .02	**.041**
pc 1 × pc 3	-.01	-.02 – -.00	**.015**			
pc 2 × pc 5	.02	.00 – .03	**.027**	.01	.00 – .03	**.031**
pc 3 × pc 5	-.03	-.05 – -.02	**<.001**	-.03	-.05 – -.01	**.004**
Ambiguity type [homonym]				.01	-.05 – .07	.746
Semantic similarity				.02	-.00 – .04	.102
Ambiguity type [homonym] × Semantic similarity				-.08	-.14 – -.03	**.002**
Random Effects						
σ^2	.05			.05		
τ_{00}	.03 Participant			.02 Participant		
	.00 Word			.00 Word		
τ_{11}	.00 Participant.trial.z			.00 Participant.trial.z		
	.00 Participant.pc_1			.00 Participant.pc_2		
	.00 Participant.pc_2			.00 Participant.pc_3		
	.00 Participant.pc_3			.00 Participant.pc_4		
	.00 Participant.pc_4			.00 Participant.pc_5		
	.00 Participant.pc_5			.01 Participant.Ambigpolyseme		
	.00 Participant.sem_sim.z			.01 Participant.Ambighomonym		
CC	.39			.29		
N	103 Participant			103 Participant		
	95 Word			95 Word		
Observations	9196			9187		
Marginal R^2/Conditional R^2	.116 / .461			.137 / .390		

Figure 4.

Effect of rated semantic similarity accros the set of stimuli (left-hand panel) and separately for homonyms and polysemes (right-hand panel) on inverse-transformed reaction latencies in Study 2a.

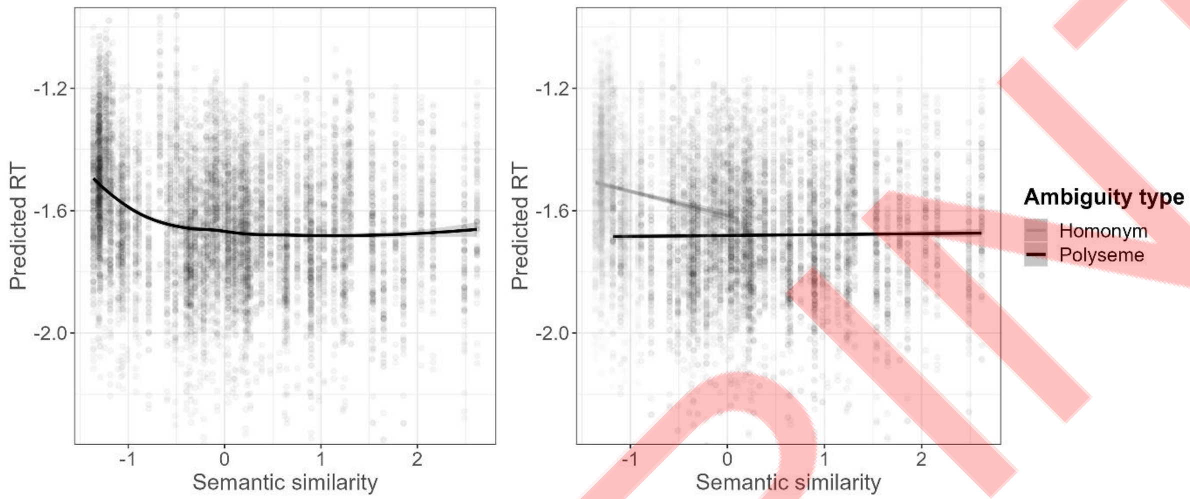


Table 4.

Model comparison of the baseline model (control variables) and the susequent models (baseline model and the key predictors) fitted to inverse-transformed reaction latencies observed in Study 2a. Numbers presented are related to the comparisson of the model in queston and the nearest model listed above it. The details of each model are listed in the note.

	Number of parameters	*AIC*	*BIC*	*logLik*	*deviance*	*Chisq*	*Df*	*p*
[a]baseline model	20	1939.2	2082.1	-949.59	1899.2			
[b]model 1 (sem.s)	21	1938.3	2088.4	-948.17	1896.3	2.845	1	.092
[c]model 2 (sm.s)	21	1940.7	2090.7	-949.35	1898.7			
[d]model 3 (sem.s)	23	1930.7	2095.0	-942.34	1884.7	14.022	1	<.001
[e]model 4 (sem.s)	24	1869.1	2040.6	-910.55	1821.1	63.581	1	<.001

[a]baseline: RT ~ 1 + trial.z + pc_1 * pc_4 + pc_1 * pc_3 + pc_2 * pc_5 + pc_3 * pc_5 + (1 | Participant) + (0 + trial.z | Participant) + (0 + pc_1 | Participant) + (0 + pc_2 | Participant) + (0 + pc_3 | Participant) + (0 + pc_4 | Participant) + (0 + pc_5 | Participant) + (1 | Word)

[b]model 1: RT ~ 1 + trial.z + pc_1 * pc_4 + pc_1 * pc_3 + pc_2 * pc_5 + pc_3 * pc_5 + **sem_sim.z** + (1 | Participant) + (0 + trial.z | Participant) + (0 + pc_1 | Participant) + (0 + pc_2 | Participant) + (0 + pc_3 | Participant) + (0 + pc_4 | Participant) + (0 + pc_5 | Participant) + (1 | Word)

[c]model 2: RT ~ 1 + trial.z + pc_1 * pc_4 + pc_1 * pc_3 + pc_2 * pc_5 + pc_3 * pc_5 + **sm_sim.z** + (1 | Participant) + (0 + trial.z | Participant) + (0 + pc_1 | Participant) + (0 + pc_2 | Participant) + (0 + pc_3 | Participant) + (0 + pc_4 | Participant) + (0 + pc_5 | Participant) + (1 | Word)

[d]model 3: RT ~ 1 + trial.z + pc_1 * pc_4 + pc_1 * pc_3 + pc_2 * pc_5 + pc_3 * pc_5 + **poly(sem_sim.z, 2)** + (1 | Participant) + (0 + trial.z | Participant) + (0 + pc_1 | Participant) + (0 + pc_2 | Participant) + (0 + pc_3 | Participant) + (0 + pc_4 | Participant) + (0 + pc_5 | Participant) + (0 + **sem_sim.z** | Participant) + (1 | Word)

[e]model 4: RT ~ 1 + trial.z + pc_1 * pc_4 + pc_2 * pc_5 + pc_3 * pc_5 + **Ambig * sem_sim.z** + (1 | Participant) + (0 + trial.z | Participant) + (0 + pc_2 | Participant) + (0 + pc_3 | Participant) + (0 + pc_4 | Participant) + (0 + pc_5 | Participant) + (0 + **Ambig** | Participant) + (1 | Word)

Given that the sensorimotor similarity was not predictive for reaction latencies, we faced two possible conclusions. On the one hand, it could indicate that sensorimotor information (as we operationalised it) was not relevant for word recognition in VLD task, which would be in oposition with ample evidence reported so far (Connell & Lynnott, 2009; Filipović Đurđević et al., 2016; Lynott & Connell, 2013; Lynott et al., 2019; Popović Stijačić, 2021). On the other hand, it could indicate that this experimental paradigm was falling short of capturing these subtle effects since, as according to some studies (Balota & Lorch, 1986; Becker et al., 1997; Joordens & Becker, 1997), it does not engage semantic processing deep enough. However, semantic processing was engaged to a certain extent, as we observed the effects of the semantic similarity for the homonymous words. The null effect of semantic similarity on VLD latencies to polysemous words could also have two causes, one of them being the nature of the task itself. Additionally, the failure to detect the effects of the relatedness of senses, both in terms of rated similarity and in terms of similarity of sensorimotor profiles, could be a consequence of the choices made during the norming phase of the study. To facilitate the data collection, we limited the number of senses selected per word. By doing this, we have not covered the full range of word senses, thus leaving out those that also contribute to the overall overlap of senses within a polysemous word. Indeed, research on the processing of ambiguous words in the visual lexical decision task suggested that processing is affected by the full range of senses (Filipović Đurđević, 2019; Filipović Đurđević & Kostić, 2008; 2023; Filipović Đurđević, Đurđević & Kostić, 2009; Mišić & Filipović Đuršević, 2023).

Study 2b: Experimental study with sensorimotor priming between polysemous senses

To assess the role of sensorimotor information more precisely, in Study 2b, we looked more closely into the specific word senses and sensorimotor experiences typically related to them, by administering a task that demands deeper semantic processing. We focused on the priming effect between the two senses of the same word and tested how the activation of sensorimotor information affected processing. We hypothesised that the activation of sensory information shared between two senses that occurred during the processing of one sense (prime) would additionally affect the processing of another sense (target), i.e. amplify the sense-priming effect. On the one hand, the prediction is rooted in the PDP models that postulate the shared core in the representation of word senses, i.e. the overlap in features that relate to multiple senses (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004). On the other hand, the prediction is driven by the well-established relevance of sonsorimotor information for representation and processing (Aziz-Zadeh et al., 2006; Chao et al., 1999; Filipović Đurđević et al., 2016; Gonzáles et al., 2006; Popović Stijačić, 2021; del Prado Martin et al., 2006; Hauk et al., 2004; Hauk & Pulvermüller, 2004; Kiefer et al., 2008; Lynott & Connel, 2013; Pulvermüller & Hauk, 2006; Pulvermüller et al., 2000; 2001; Simmons et al., 2005; 2007) and by the results of Study1a and Study1b that demonstrated the relevance of sensorimotor information for the representation of lexical ambiguity.

To test our hypothesis, we created an experience verification task and applied the experimental paradigm of continuous priming. We nested polysemous words in syntagms that dissambiguated polysemous senses (e.g. *sealed letter*) and presented participants with short phrases that described a certain sensory experience (e.g. *have seen a sealed letter*). The participants were instructed to evaluate if they had ever had the experience in question. The phrases were presented continuously to the participants (one at a time), but were arranged in prime-target pairs of identical sensory experience with two different senses of the same polysemous word. In half of the trials, the phrases referred to the sensory experience common to both senses (e.g. *have seen a sealed letter, have seen an italic letter)*, thus activating the shared core during processing of a prime. However, in half of the trials, the phrases referred to the sensory experience that is related to the prime, but not the target (e.g. *have touched a sealed letter, have touched an italic letter*), thus failing to activate the shared core. Because the expected sequence of responses to prime and target was *yes-yes* in the former condition, and *yes-no* in the latter condition, we also controlled for the effects of response-mapping and response-switching by introducing control conditions with the same sequences of responses, but without the priming between the senses.

To summarise, we predicted the main effect of the response mapping/switching (shorter latencies to targets for yes-yes than for yes-no responses) and the main effect of sense priming (shorter latencies for targets preceded by the related sense as the prime). However, our crucial prediction was related to the interaction between the two factors. We predicted that the sense-priming effect would be larger when the sensory experience in queston was shared between prime and target, i.e. when sensory experience activated during the processing of the prime was also relevant for the processing of the target (as compared to the condition when it was only relevant for the processing of the prime).

Method

Participants

The novel group of 123 first-year psychology students at University of Belgrade was recruited. All participants signed informed consents (Following the Protocol #2023-65, approved by the Institutional Review Board of Department of Psychology at the Faculty of Philosophy, University of Belgrade). The number of participants was estimated following recommendations of Brysbaert and Stevens (2018).

Materials and design

Our experiment followed a 2x2 factorial design. The first factor was Modality (shared/unique), and the second factor was Priming (primed/non-primed).

To manipulate Modality, we selected a total of 40 Serbian polysemous nouns from the available databases (Filipović Đurđević & Kostić, 2017; Mišić et al., 2024; Popović Stijačić, 2021) and the Matica Srpska Dictionary of the Serbian language (Matica Srpska, 2011). For each noun, we selected a pair of senses to fit our experimental design. Disambiguation, i.e. referring to one specific sense, was achieved by placing a polysemous noun in a syntagm (e.g. *a music album* or *a photo album*). Finally, we created the stimuli by nesting the syntagm into a phrase that included a verb referring to a sensory modality (e.g. *have seen a music album*[1]). A prime stimulus and a target stimulus always contained the same verb, i.e. always referred to the same sensory modality. In half of the crucial trials, modality was *shared* among both senses, i.e. both experiences (denoted by the prime and by the target) were possible (e.g. *have seen a music album –have seen a photo album*). In another half, the modality was *unique* for the prime only, i.e. the experience denoted by the prime was possible, and the one denoted by the target was not (e.g. *have heard a music album – have heard a photo album*).

To manipulate priming, we created a parallel list, in which we paired each target sense with a neutral stimulus/task. In the control trials (i.e. non-primed trials), a filler stimulus was presented as a prime stimulus, where participants had to verify if the sentence was true, given the position of letters shown next to it (e.g. *A is preceded by B. AB;* Baddeley & Hitch, 1974). To control for the mapping of the responses and the response switching, we matched the filler-target pairs and prime-target pairs for the sequence of the expected responses (yes-yes and yes-no).

To control for the transfer from one prime-target pair to another, between every prime-target pair (and/or filler-target pair), a filler stimulus (verification sentence) was presented (e.g. *A is preceded by B. AB*). In non-primed pairs, a filler stimulus and a prime stimulus were never the same, and the verification sentences were randomly assigned to a filler and a prime group. However, from the participants' point of view, they have been presented with one long random sequence of phrases and tasks, with the pairs' boundaries not obvious.

In order to prevent participants from incidentally learning that one word sense is always followed by another sense of the same word, besides the 40 crucial stimuli pairs, another 20 stimuli pairs consisting of different words were included (e.g. *seen a guitar string – seen a kitchen table*), words in those pairs were different from words used for the crucial 40 pairs.

Additionally, to account for the large disparity between the number of expected affirmative and negative responses, an additional 10 sense pairs and five word pairs were

[1] In the Serbian language, *have seen* would translate differently for male and female participants (*video* and *videla*), so the two parallel experimental files were created and chosen according to the participant's gender. The same goes for other sensory verbs as well.

added where a negative response is expected for both the prime and target stimulus. The filler stimuli consisting of sentences and letter patterns (*A is preceded by B. AB*) were also constructed so that the total number of expected affirmative and negative answers was the same accross this set, as well.

Finally, in order to counter-balance items and participants across the four conditions (shared primed, shared non-primed, unique primed, and unique non-primed) by using a Latin sqare design, we created four parallel experimental lists of our crucial stimuli (40 pairs).

Procedure

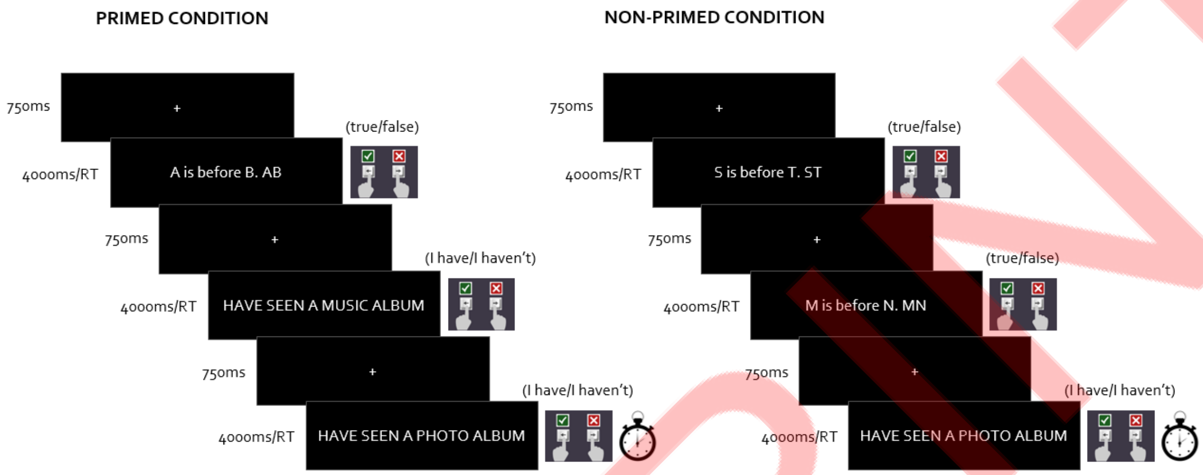
The experiment was conducted using OpenSesame version 4.0.5 Melodramatic Milgram (Mathôt et al., 2012; Supplementary Materials 12) on the desktop computer in the laboratory with the experimenter present.

The stimuli were presented sequentially on the computer screen (one at a time), and the participants were instructed to engage in two randomly sequenced tasks: to evaluate whether they ever had a described experience, e.g. [*Have you ever*] *seen a music album* (if presented with such a phrase), or to verify if the sentence was true concerning the letters presented next to it, e.g. *A is preceded by B. AB (*if presented with such a set). The responses (yes/no) were mapped onto the left and right arrow keys (participants were instructed to hold their index fingers above those keys during the session), and the mapping was counterbalanced across the participants. The order of trial presentation was randomised individually for each participant, but the sequence of stimuli within a trial was fixed in advance (see Figure 4). Although responses and reaction latencies were recorded for all stimuli, the reaction latencies of the main interest were only those elicited by the target. The responses to the primes and targets were used for filtering (to include only the trials with the relevant pattern of responses).

Each trial began with a fixation point that was presented for 750ms at the center of the screen, followed by a filler stimulus (sentence about letters) that remained on the screen until the response and maximally for 4000ms. It was followed by another fixation point (750ms), prime/filler stimulus (until response/4000ms), than another fixation point (750ms) and a target stimulus (until response/4000ms). The full sequence of the stimuli within a trial is illustrated in Figure 5.

Figure 5.

Schematic representation of the sequence of stimulus presentation within a trial. The example illustrates the shared modality condition, both for the primed (left-hand side) and the non-primed conditions (right-hand side).



Results & Discussion

The analysis was conducted in R statistical software (R version 4.2.2; R Core Team, 2022), using packages lme4 (Bates et al., 2015), sjPlot (Lüdecke, 2021), lmertest (Kuznetsova et al., 2017), ggplot2 (Wickham, 2016), dplyr (Wickham et al, 2023); see Supplementary Materials 13. Prior to analyses, we excluded 21 participants (~17% of the initial 123 participants) that did not meet the 75% accuracy criterion on either prime, target, or filler stimuli. Then, after filtering out filler stimuli, we excluded 10 of our crucial stimulus pairs (25% of the initial 40 pairs) that didn't meet our 75% accuracy criterion as either the prime or the target stimuli (or both).

Additionally, we filtered out those trials where responses to either the prime or the target were opposite to the expected response; e.g. if we included *tasted a chocolate bar* as a stimulus and, by the design, expected a positive answer to it, if a participant had never tasted a chocolate bar and hence answered *no*, we would exclude that trial (both the prime and the target). Although those answers are not incorrect per se, we treated them as such, as they deviated from our expected experimental design (and the typical responses we would expect based on the common native-speaker intuition) and thus were not diagnostic regarding our main research question.

The main analysis was conducted on the log-transformed response latencies for the target responses (to account for the skewed distribution).

In the next step, we built a linear mixed-effects regression model by including as fixed effects both the priming condition (primed/non-primed) and the modality type (shared/unique), as well as the trial order. Starting from the maximum structure allowed by the design (as suggested by Barr et al., 2013), random effects were excluded from the structure as justified by the data, according to the successive model comparison and the RePsychling package (Bates et al., 2015b; Matuschek et al., 2017). The final model was refitted by excluding the residuals that were outside of the -2.5/2.5 range (to control for the influential datapoints). The structure of the effects was not affected by this procedure, and we therefore report the refitted model.

The results (Table 5) revealed the significant fixed effect of the order of trial presentation, which indicated that the participants were gaining in speed during the course of the experiment, as would be predictable given the novelty of the task and the complexity incurred by task switching (they were adapting to the task). Both of the main effects were significant, so that targets preceded by the related sense as a prime were responded to faster than the ones preceded by the filler stimulus (β = -.15, CI [-.17 – -.12], t = -12.203, $p < .001$) and the targets referring to the shared modality were processed faster compared to the ones referring to the unique modality (β = .09, CI [.07 – .11], t = 7.601, $p < .001$). However, the most important finding is that the priming effect was larger in the shared modality condition, i.e. the interaction was significant (β = .04, CI [.01 – .08], t = 2.430, $p < .05$), as illustrated in Figure 6.

Figure 6.

Interaction of priming and modality type on log-transformed reaction latencies, as predicted by the best-fitting linear mixed-effects model in Study 2b.

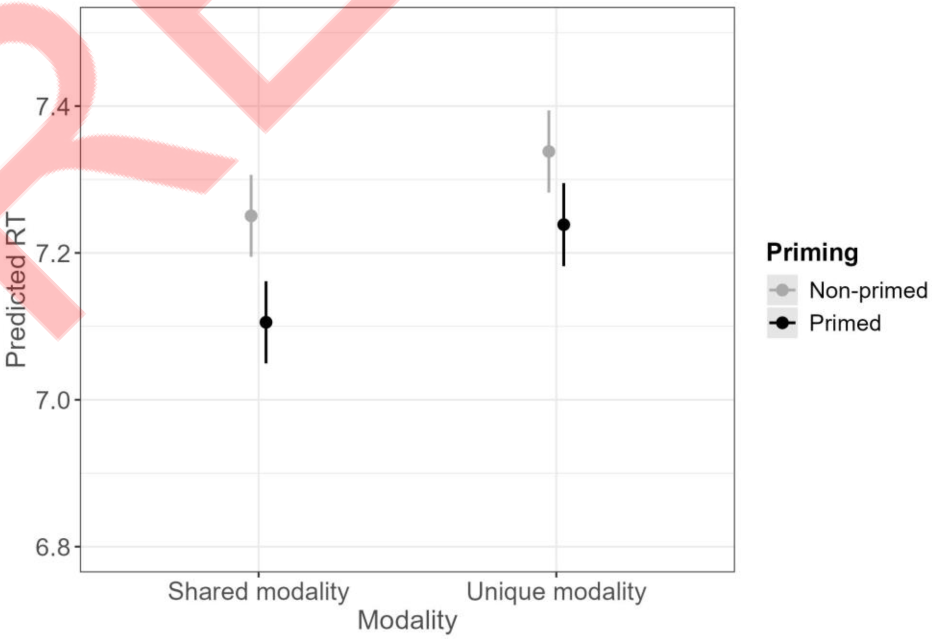


Table 5.

Coefficients obtained in the best-fitting model fitted to log-transformed reaction latencies observed in Study 2b.

Predictors	*Estimates*	*CI*	*p*
Intercept (Modality [Shared]; Priming [Non-primed])	7.28	7.22 – 7.34	**<.001**
Order of trial presentation	-.00	-.00 – -.00	**<.001**
Modality [Unique]	.09	.07 – .11	**<.001**
Priming [Primed]	-.15	-.17 – -.12	**<.001**
Modality [Unique] × Priming [Primed]	.04	.01 – .08	**.015**
Random Effects			
σ^2	.05		
$\tau_{00\ Participant}$	.03		
$\tau_{00\ Word}$	.01		
ICC	.49		
$N_{Participant}$	102		
N_{Word}	30		
Observations	2493		
Marginal R^2 / Conditional R^2	.081 / .532		

To sum up, in Study 2b, we showed that sensorimotor information had an expected role in semantically engaging processing of polysemous senses. Namely, when participants engaged in the experience verification task, i.e. when they had to evaluate if they had ever experienced the object in question, the verification was faster when the denoted experience was previously boosted by the other object that shares the experience with the verified one. Because the two objects were denoted by the two related senses of the same polysemous word, we expected the facilitation by the presentation of the related sense, and we did observe it. The other main effect observed, i.e. the faster verification of the target in the shared condition, is the consequence of the response switch in the unique modality condition. Because the experience was unique to the prime only, the expected response was positive for the prime and negative for the target, hence producing the response switch, while in the shared condition, there were two consecutive positive responses. This effect is therefore the methodological artefact that we controlled for by our experimental design, i.e. selecting the corresponding filler stimuli. However, this effect shouldn't be mistaken for the modality switch effect, as a prime and a target always referred to the same sensory modality (Pecher et al., 2003). Nevertheless, our crucial effect, the stronger priming effect in the shared condition, can only be attributed to the effect of the shared modality. This suggests that sensorimotor information modulates the priming effect depending on the aspect of meaning it reflects – whether it is something shared among senses or something unique for one sense only.

General discussion

In this research, we brought together the framework of embodied cognition (Barsalou, 1999; 2008; 2010; Meteyard et al., 2012) and the models of lexical ambiguity (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004). We conducted four studies to shed light on the long-neglected status of sensorimotor information in the representation and processing of ambiguous words. We collected sensorimotor norms for individual meanings/senses of ambiguous words and demonstrated that linguistic distinction between polysemy (as a form of lexical ambiguity where a single form is mapped onto a set of related senses) and homonymy (mapping of a single form onto a set of unrelated meanings) was reflected in the sensorimotor experience with the objects denoted by different senses/meanings of ambiguous words. Next, we showed that the captured sensorimotor information was related to the semantic dimension of representation. Although the sensorimotor description of the set of senses/meanings failed to affect the shallow process of word recognition, we demonstrated that in a more semantically engaging task, the activation of the appropriate sense benefited from the preactivation of the appropriate sensorimotor domain. This finding contributed to the view that representations of related polysemous senses overlap (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004) and that sensorimotor information can serve the role of the units of representation postulated by the PDP framework. We thus showed that the framework of embodied cognition can be a fruitful ground for testing the debates concerning the representation of ambiguous words, but we also demonstrated that lexical ambiguity should be taken into account when collecting sensorimotor norms.

The first two studies corroborated that semantics was reflected in the sensorimotor information and extended this insight onto lexical ambiguity. Namely, related senses of polysemous words are shown to be not only semantically more similar, but also more similar in the sensorimotor domain, i.e. to have more similar sensorimotor profiles compared to the unrelated meanings of homonyms. For example, both *daily paper* and *wrapping paper* can be experienced in visual, tactile, and olfactory domains (but not in auditory and gustatory), whereas *dog bark*, unlike *tree bark*, can be experienced in the auditory (but not visual, tactile, etc.) domain. In addition to such categorical distinction between polysemy and homonymy, this relationship was also captured using continuous variables, by registering a positive correlation between the ratings of semantic similarity among senses/meanings and similarity measure derived from their sensorimotor profiles. On the one hand, this finding captured a more fine-grained differentiation of senses/meanings, potentially capturing the gradual shift from homonymy to metaphor, then metonymy, etc. On the other hand, it demonstrated that the variation reflected in sensorimotor profiles was semantic in nature. Therefore, as predicted, sensorimotor features coded some aspects of ambiguous word meaning representation. This finding is in line with the observations from two similar studies that reported a positive correlation between sensorimotor and semantic similarity of words as unitary concepts (treated as unambiguous, without denoting a particular meaning/sense; Speed & Majid, 2017; Wingfield & Connell, 2023).

The remaining two studies showed that, although not present in shallow processing of words presented in isolation, the effect of sensorimotor information was evident in deeper semantic processing that demanded access to separate word senses, i.e. processing of ambiguous words nested within the disambiguating context. Namely, in the lexical decision task, where ambiguous words were being presented in isolation, without pointing to a specific meaning/sense, the sensorimotor similarity of meanings/senses of one word was not shown to be predictive for reaction latencies. This finding was unexpected, considering the research in which semantic similarity, as operationalised through ambiguity type categories, was found to be relevant. In those studies categories of words with higher level of relatedness (such as metonymy) were processed faster than categories of words with lesser relatedness (such as metaphors, then homonyms, etc; Armstrong & Plaut, 2008; 2011; Beretta et al., 2005; Klepousniotou & Baum, 2007; Rodd et al., 2002). However, a recent finding demonstrated that a particular design (simultaneous presentation of two words to minimise the time gap between the stimuli) was needed to detect sensorimotor effects in LDT (Platonova & Miklashevsky, 2025). Nevertheless, the role of sensorimotor information in polysemous words processing was evident in our novel continuous priming experience verification task that was more semantically engaging, where participants evaluated if they had ever experienced the object in question (a specific sense of a polysemous word) within a specified modality. In line with some previous studies (Brown, 2008; Klepousniotou et al., 2008; Williams, 1992), we observed facilitation by the presentation of the related sense (but see Klein & Murphy, 2001 for the null effect of related prime). Crucially, the priming effect between two polysemous senses was stronger when both senses were consecutively evaluated on the sensory experience that both senses share, i.e. when a shared feature was highlighted, compared to the condition in which the modality that is unique for one sense only (that of a prime) was highlighted. It is important to note that this effect cannot be attributed to the presence (vs absence) of the modality switching (Pecher et al., 2003), because the modality was never switched within a pair of senses. The switching occurred in the domain of responses (yes-yes in case of shared modality vs. yes-no in case of prime-unique modality). Nevertheless, the crucial effect cannot be attributed to this either, as we controlled for the effect of response-switching using experimental design and observing the prime by modality-sharing interaction (the main effect of prime can be attributed to sense priming, the main effect of modality-sharing could be attributed to response-repetition, but the interaction can only be attributed to the effect of shared modality). This finding revealed not only that sensorimotor information took a role in processing ambiguous words, but also that sensorimotor information was an integral part of the representation of meaning that affected the disambiguation process. Sensorimotor information behaves like the basic units (from PDP models; Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004) – their activation mimics activation of basic units, it is part of the meaning activation, and it facilitates processing.

This research is rooted in two theoretical frameworks, embodied cognition models and lexical ambiguity models, that seem to shed light on different, but complementary, aspects of mental representation of word meaning. Regarding the embodied cognition models, our findings both corroborate and broaden their assumptions. Namely, given that they postulate that sensorimotor information is the foundation of the meaning of a word (Barsalou, 1999; 2003), it is conceivable that the sensorimotor profile would be attuned to subtle differences in meaning. In the context of our research, it would be expected that the sensorimotor profile obtained for a word (e.g. *mouse*) could not directly mirror all of the different senses/meanings of that word (e.g. *mouse [for computer]* and *mouse [animal]*). In this regard, it would be expected that the greater divergence in the meanings of two meanings/senses would be accompanied by greater divergence in sensorimotor profiles. As we identified the difference in the similarity of sensorimotor profiles across the semantic continuum, our findings suggest that sensorimotor experience at least partially constitutes the representation of concepts.

On the other hand, lexical ambiguity theories have so far focused mainly on the structure of the representation depending on the lexical ambiguity type – homonymy and polysemy (regular and irregular; Apresjan, 1974). Assumptions were mainly given about the relationships among the representations of meanings/senses within a word and the dynamics of their activation during the disambiguation process. One of the core debates was related to the separation of the representations of meanings/senses. Whereas the agreement was achieved that homonymous meanings have separate representations, the nature of the representations of polysemous senses has been debated. Some argued that they mimicked the representation of homonymy (Klein & Murphy, 2002), whereas others advocated for the existence of the shared core in polysemy representation (Armstrong, 2012; Armstrong & Plaut, 2016; Rodd, 2018; 2020; Rodd et al., 2004). Our results speak in favour of the latter, corroborating that representations of polysemous senses partially overlap and suggesting the existence of the shared core accompanied by the additional representation unique to individual senses. Moreover, our finding of the facilitatory effect of the semantic similarity between the homonymous meanings on the processing of homonyms challenges the claim that even these representations are independent. However, lexical ambiguity theories have so far mostly neglected the discussion about the nature and origin of the hypothetically postulated basic units. Especially, they have failed to explicitly take into consideration the experiential aspect of the meaning, that represents the central idea of the embodied cognition models. Therefore, our findings inform PDP models that the basic units whose patterns of activation constitute mental representation could be sensorimotor in nature as well. We therefore contributed to the pursuit of the epistemological status of the basic units in PDP models.

Although we demonstrated the importance of sensorimotor information for the processing of ambiguous words, there remains an important, recently introduced debate that our experimental design can not address – the debate concerning the locus of the contextual priming effect. According to the immediate alternation account (Gilbert et al., 2018; Rodd et al., 2013; 2015), processing of the prime leads to immediate updating of the representations in the semantic memory. On the other hand, the newly introduced episodic context account proposes that the exposure of the ambiguous word in a sentence creates a temporary episodic trace by binding the words in a meaningful unit that biases participants toward a certain interpretation of the target sense (Gaskell et al., 2019; Gaskell, 2024). Therefore, the impact of preactivation of the shared sensorimotor information could lead to activation of shared long-term representations in semantic memory, but also to the creation of temporary representations in episodic memory. Although further studies are needed to resolve the precise mechanism of the effect, the finding of the relevance of the sensorimotor information for the lexical ambiguity (and vice versa) remains. Moreover, it opens a new avenue for this line of research.

Along with the described theoretical contributions and novelties, this research fills the empirical gap as well. As far as we are aware, there is only one study that has collected what we call ambiguity-sensitive sensorimotor norms, i.e. what they call contextualised sensorimotor judgments (Trott & Bergen, 2022). Our finding regarding the positive relationship between sensorimotor similarity and semantic similarity is in line with the negative relationship between sensorimotor distance and rated relatedness that Trott and Bergen (2022) registered. However, their focus was on the evaluation of large language models, whereas in our research, additional experimental data and theoretical interpretations give a deeper understanding of the relationship between embodied cognition models and ambiguity theories.

Although not directly related to the main goal of the study, an additional novelty of our study lies in the contribution to the procedure of collecting sensorimotor norms. Specifically, the dimension of motor experience using the head was divided into two different scales: using the head as a physical body part in interacting with objects and using the head as a mental structure in thinking about objects/ideas, as it had been suggested in the Lancaster Sensorimotor Norms paper (Lynnott et al., 2019).

This study, although among the first to collect sensorimotor ratings for separate senses, and the first to directly test the role of SM information in ambiguity representation and processing, is not without limitations. Primarily, the distributions of both similarity measures deviate from the normal distribution, so using nonparametric tests was necessary. Since more than two-thirds of our stimuli were polysemous and since polysemous pairs were more sensorimotorly similar, it seems clear why we observed a negatively asymmetrical distribution of the sensorimotor similarity measure. However, this cannot explain the observed positively asymmetrical distribution of semantic similarity measures. We offered one possible methodological explanation to account for the finding, but further studies are needed to shed more light.

To conclude, our research provided one attempt to reconcile PDP models of lexical ambiguity and embodied cognition models. The findings both confirm and broaden these two groups of models by indicating the relatedness of semantic and sensorimotor aspects of mental representation, as well as showing the role of sensorimotor information in the processing of linguistic material.

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The authors have no known conflict of interest to disclose.

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