research papers

Motor and Auditory Priming in a Lexical Decision Task with Action and Sound Verbs

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Abstract. According to embodied cognition theories, concepts are represented in sensory and motor brain systems. These sensory-motor representations can give rise to priming effects. Action verbs (e.g., *to push*) presumably have a higher association with motor features, and sound verbs (e.g., *to buzz*) with auditory features. This study assesses whether motor and auditory primes differentially influence the lexical decision of action and sound verbs. Seventy-five healthy Russian-speaking adults participated in the experiment. An online lexical decision task with cross-modal priming was administered. Participants were presented with meaningless primes such as a video clip of a moving hand (motor prime), a bike bell sound (auditory prime), or a static video clip (neutral prime). Then they saw a verb (an action verb, a sound verb, or a pseudoverb) and had to report whether or not it was a real word by pressing a button on the keyboard. Linear mixed effect models indicated no effect of the prime type on response accuracy or speed for any verb type. However, intransitive verbs elicited less accurate responses than transitive and optional-transitive verbs overall, regardless of the prime type. Moreover, participants responded slower for pseudoverbs than for real verbs. The results do not suggest differential category specific effects for action- and sound-related verbs in a lexical decision task. However, the results for intransitive verbs support the facilitation through complexity hypothesis. Our findings do not support embodied cognition theories, but await further replication. Recommendations and future directions are discussed.

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Introduction

The theory of embodied cognition claims that the brain areas involved in sensory and motor experiences are activated when linguistic material related to those experiences is processed. This, in effect, supports the existence of perceptual symbol systems (Barsalou, 1999). Under this view, perceptual states in sensory-motor systems are *extracted* and stored as perceptual symbols in long-term memory. These perceptual symbols are modal in nature, since they are represented in a system responsible for the corresponding perceptual states, and at the same time analogical, as their structure is similar to that of the original perceptual states. This symbol formation process involves different aspects of perceived experience: the sensory modalities (i.e., vision, audition, haptics, olfaction, and gustation), as well as proprioception and introspection. As a result, different symbols are stored in brain areas in the motor and/or auditory cortex, for example.

Perceptual symbol systems were proposed in contrast to the traditional amodal symbol systems, according to which perceptual states in the sensory-motor systems are *converted* into a new representational system (Barsalou, 1999). These new symbols are amodal, as they do not have any correspondence with the perceptual states, and arbitrary, due to their conventional associations with the referent (see Figure 1; Barsalou, 1999).

An experimental framework that embraces the three components essential for embodiment (i.e., perception, action, and cognition) is priming (see *Priming and cross-modal experiments section*): the effect that perceiving a certain stimulus or prime first *(perception)* can have on a reaction to the stimulus or target that is seen later *(action)*. This evidence can be used to shed light on *cognition*.

In an effort to reliably test the nature of concept representations, Kiefer, Sim, Herrnberger, Grothe, and Hoenig (2008) suggested that (1) the administered task has to implicitly retrieve conceptual features, for example by incorporating a lexical decision task; (2) it should activate the perceptual brain region in order to identify the overlap between conceptual and perceptual processing; and (3 and 4) brain areas should respond rapidly and selectively, in order to exclude any post conceptual strategic process occurring after a concept has been fully accessed. The time required to make a lexical decision and its accuracy give an estimation of the operations needed to access the lexical representation. Remarkably, pseudowords, even though they contain less information compared to words, are classified more slowly, but not less accurately; this difference has been argued to be due to the conflict arising between the incorrect response ("yes, it's a word") and the correct response ("no, it's not a word") (Carreiras, Mechelli, Estévez, & Price, 2007). In addition, response time and accuracy are also affected by the context provided (e.g., a prime). Finally, a visual lexical decision task requiring a finger press response brings an increased activation in manual responses (Carreiras et al., 2007): it is necessary to keep that in mind when testing the nature of hand-related concepts. The current study will examine the representation of a specific category of concepts, the one related to verbs.

Verbs and Embodied Cognition

Verbs represent predication, describing events and relations among entities. Differences within verbs are based on grammatical (i.e., transitivity, number of arguments, regularity),

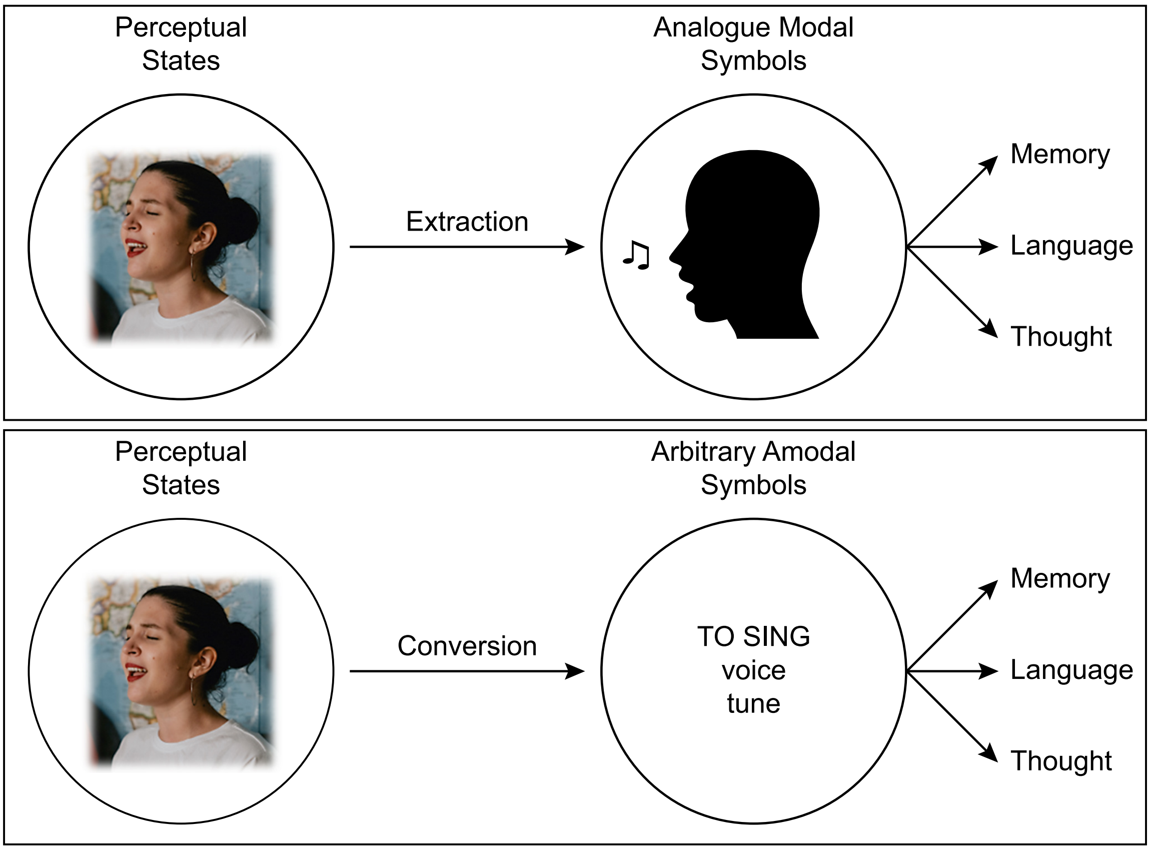

Figure 1. Perceptual and amodal symbol systems. Perceptual (above) and amodal (below) symbol systems represented for the verb "to sing". Linguistic forms are typically used to represent amodal symbols. Based on Barsalou (1999).

conceptual lexical (i.e., relatedness to a noun, familiarity, age of acquisition, word length, frequency) and conceptual semantic (i.e., instrumentality, imageability, concreteness) variables. All these factors may play a role in their different processing loads, timing of acquisition, vulnerability in brain damage, and language mapping procedures. In particular, verb argument structure is a grammatical aspect, and transitivity is an example of a feature related to argument structure, which affects the processing of verbs. According to the *argument structure complexity* hypothesis (Thompson, 2003), verbs with a higher number of arguments are more difficult to process (Thompson, Lange, Schneider, & Shapiro, 1997; Barbieri, Aggujaro, Molteni, & Luzzatti, 2015). Recently, the *facilitation through complexity* hypothesis (Malyutina & den Ouden, 2017) added that the argument structure of verbs has different effects depending on processing conditions. In a single-word task, the argument's complexity, by providing more routes of verb access, might play a facilitatory role; meanwhile, in a sentence-level task, the verb's argument structure takes on a negative role as additional morphosyntactic demands come into play. Thus, verb argument structure must be taken into account when studying verbs.

The features referring to conceptual semantics represent the major interest in the embodied cognition framework. For the purposes of this study, concrete concepts, the ones related to an immediate sensory-motor experience, are taken into account. This presents a certain challenge. While most adjectives are associated with a distinct sensory-motor modality — olfactory (e.g., *fragrant*), visual (e.g., *bright*), motor (e.g., *quick*), haptics (e.g., *soft*), hearing (e.g. *silent*) — it is hard to find verbs mainly entailing a sensory experience, rather than a motor one. Taking this problem into consideration, in this study we will focus on two very distinct types of verbs: action verbs and sound verbs.

Action verbs are characterized by a closer association with the motor feature compared to other conceptual features (e.g., auditory, visual) (see Figure 2).

Many studies have focused on action verbs, particularly those associated with specific body parts. For instance, in a functional magnetic resonance imaging (fMRI) study by Hauk, Johnsrude, and Pulvermüller (2005) the passive reading of action words referring to face, arm, or leg actions (e.g., to lick, pick, or kick) was shown to activate motor areas that seem to overlap or be adjacent to the activation areas observed for the actual movement of the tongue, fingers, or feet. Similar results have been found during passive listening to sentences that include some action of the mouth, hands, or legs (Tettamanti et al., 2005). Therefore, action words are defined as *semantic links*, as they bind language and action in the brain: stimulation of the motor sites (e.g., via TMS) has been shown to influence the processing of verbs that are semantically related to these areas (e.g., 'to kick' and the leg area of the motor cortex) (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005).

The current study compares action verbs with sound verbs, which are those with a higher association with the auditory feature compared to other conceptual features (e.g., motor, visual) (see Figure 3).

Fewer studies have focused on sound verbs. Studies on human action sound identification have shown that the processing of human sounds activates the action-sound network, while sounds produced by non-living sources activate areas related to visual form, feature, and object recognition (Engel, Frum, Puce, Walker, & Lewis, 2009; Lemaitre et al., 2018). Notably, a category-preferential organization for processing real-world sounds has been supported by dissociations of activated cortical networks for human (e.g., applause), animal (e.g., buzzing insect), mechanical (e.g., egg timer), and environmental (e.g., heavy rain) sound-sources (Engel et al., 2009).

Overall, studies reporting the semantic somatotopy of action verb processing, together with those showing a category-preferential organization for processing real-world sounds, give reason to suspect the embodiment of sound verbs as well. On the other hand, experiments including both action and sound verbs seem to not totally support the embodiment of verbs, unless an explicit task is used (Popp, Trumpp, & Kiefer, 2016; Popp, Trumpp, & Kiefer, 2019; Popp, Trumpp, Sim, & Kiefer, 2019). However,

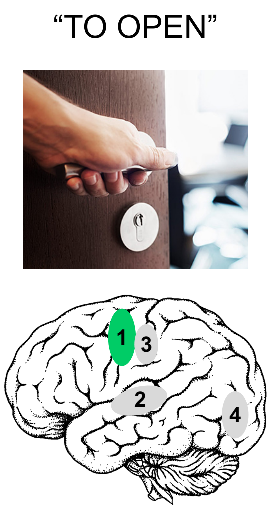

Figure 2. Neural correlates of action verb processing. The meaning of action verbs, in this case "to open", might be grounded in the motor cortex (1). Second, it might be linked to auditory cortex (2), somato-sensory cortex (3), visual cortex (4). Based on Buccino et al. (2019).

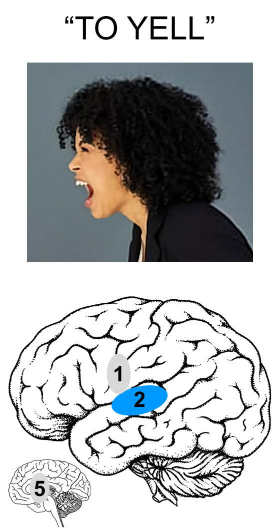

Figure 3. Neural correlates of sound verb processing. The meaning of sound verbs, in this case "to yell", might be grounded in the auditory cortex (2). Second, it might be linked to motor cortex (1) and emotion-related brain regions (5). Based on Buccino et al. (2019).

the included stimuli were simply labeled as action or sound verbs, without considering, for the action verbs, whether they were executed by a mouth, hand, or foot.

Cross-Modal Priming Experiments

Cross-modal priming experiments have shown that encoding an iconic gesture activates semantically related words (So, Low, Yap, Kheng, & Yap, 2013; Yap, So, Melvin Yap, Tan, & Teoh, 2011). Concerning action verbs, Murteira, Sowman, and Nickels (2019) used a pantomimed gesture as a prime and action verb retrieval as the target. They found faster responses when the action picture was preceded by a gesture that was congruent (representing the same action) compared to an incongruent one (representing an unrelated but meaningful action). On a similar line, Klepp, Van Dijk, Niccolai, Schnitzler, and Biermann-Ruben (2019), using magnetoencephalography, created an experiment combining action verbs related to hands and feet with response effectors (hand and foot). Congruent verb-response conditions were associated with faster reaction times, offering evidence for a somatotopic verb-motor priming effect. However, the effects of facilitation (or inhibition) that action-language processing has on motor responses (and vice versa) depends on different factors, such as the type of task employed, the stimuli administered, and the timing of stimuli presentation (Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012; Sato, MeHarrisngarelli, Riggio, Gallese, & Buccino, 2008; García & Ibáñez, 2016;).

To the best of our knowledge, no studies have investigated cross-modal priming using the same unspecified primes in visual and auditory modalities.

Aim, Research Questions, Hypotheses and Predictions

The aim of this study was to assess whether motor and auditory primes differentially influence lexical decisions of action and sound verbs.

To do so, we ran a cross-modal priming study to answer whether the previous exposure to a motor or auditory prime affects the speed and accuracy of lexical decisions for action-related vs. sound-related verbs.

We did not indicate a specific direction for accuracy and reaction times because the primes do not specifically repeat the whole target concept (e.g., the verb *to moo* is not preceded by a *moo sound* as prime). As a result, they might behave as repetition priming (i.e., facilitation), making the target processing faster or more accurate, or as interference (i.e., inhibition), making the target processing slower or less accurate. For instance, an unspecified hand movement is followed by an action verb such as *to wash*, with which it has in common only the feature that it is an action performed by a hand; the bike bell sound is followed by a sound verb such as *to sing*, with which it has in common only the auditory feature.

An interaction between perceptual and linguistic processing (i.e., action prime with action verb, and acoustic prime with sound verb) would support the idea the action prime and action verbs are represented, to some extent, in the motor cortex; whereas the auditory prime and sound verbs are represented, to some extent, in the auditory cortex. Consequently, it would support the embodied cognition views.

Method

Participants

Seventy-five volunteers (24 males; ages 18 to 77 years, $M = 29$, $SD = 12.28$) were recruited using online advertisements on social media sites (e.g., Facebook) and word-of-mouth. A total of six participants were excluded because they did not meet the inclusion criteria: three had neurological disorders, two had poor eyesight, one had poor eyesight and poor hearing. Sixty-nine participants (list A: 33; list B:36) were then included in the data analysis (21 males; ages 18 to 77 years, $M = 28.5$, $SD = 11.74$). They were all Russian native speakers (3 were bilingual native speakers of Ukranian or Tatar), with normal or corrected-to-normal vision and normal hearing, without history of neurological (including reading and motor impairments) or psychiatric disorders according to an online form. According to the short form of the Edinburgh Handedness Inventory (Veale, 2014), 58 (84 %) participants were right-handed ($M = 86.3$, $SD = 14.7$), 10 (14.5 %) were ambidextrous ($M = 25$, $SD = 31.1$), and one (1.5 %) was left-handed (score = –75). In terms of education, 61 individuals obtained a university degree, seven completed high school and one did not complete high school. Thirty five participants (51%) declared that they play video games (this information was collected due to the related enhanced perceptual and motor skills, including visual/spatial processing and hand-eye coordination; Powers, Brooks, Aldrich, Palladino, & Alfieri, 2013).

Informed consent was obtained through an online form, and participants were told of the possibility to opt out during the experiment. Participation was voluntary and no financial compensation was provided. The procedure was approved by the Research Ethics Review Committee (*Commissie Ethische Toetsing Onderzoek*, eCETO) of the University of Groningen, The Netherlands.

Stimuli and Stimuli Preparation

To avoid any grammatical class ambiguity, the language chosen was Russian, in which verbs are clearly marked by their endings (i.e., -ть, t'). The experimental paradigm consisted of three types of stimuli: 48 action verbs (e.g., толкать, tolkat', *to push*), 48 sound verbs (e.g., храпеть, khrapet', *to snore*), 96 pseudowords (e.g., надбыть, nadbyt'); hence the total number of stimuli was 192 (see Appendix A). Pseudoverbs were generated using an algorithm broadly based on principles described in Keuleers and Brysbaert (2010): they were letter strings conforming to the orthographic and phonological patterns of Russian. Pseudoverbs were matched phonologically as well as by length in graphemes and frequency (that is, each pseudoverb was generated from a list of verbs having a specific range of frequency) with their verb counterparts.

Prior to the creation of the experimental paradigm, we obtained word properties for 160 Russian verbs. To do so, we used two different procedures, including:

i) A Google Forms survey (Смыслы и ассоциации, Smysly i assotsiatsii, *Meanings and associations*), which was shared on social networks (e.g., Facebook). Its completion took around 10-15 minutes. The survey was completed by 140 healthy individuals (32 males; ages 18 to 72 years [$M = 37.1$, $SD = 13.6$]) and was used to obtain ratings for

Table 1. Transitivity and Instrumentality Across Lists

		Action Verbs			Sound Verbs		
		List A	List B	Total	List A	List B	Total
Transitivity	Transitive	13	11	24	1	0	1
	Can be both	11	13	24	9	10	19
	Intransitive	0	0	0	14	14	28
Instrumentality	Instrumental	6	8	14	0	0	0
	Can be both	5	6	11	1	0	1
	Not instrumental	13	10	23	23	24	47

the relevance of visual, action, sound, and emotional features, and their familiarity. An emotional rating was included due to the facilitatory role that emotional valence has in the processing of verbal stimuli (Kousta, Vinson, & Vigliocco, 2009). Visual and sound ratings were obtained following the instructions given by Paivio et al. (1968) while action, emotional, and familiarity ratings followed Popp et al. (2016). The verbs were rated on a five-point Likert scale (one = low familiarity/relevance; five = high familiarity/relevance).

The survey contained 80 hand-related action verbs (mean number of letters = 6.94) including 28 actions made with a tool (e.g., ковать, kovat', *to hammer*), 34 actions made with a hand (e.g., трогать, trogat', *to touch*), and 18 actions that can be made by both (e.g., открывать, otkryvat', *to open*); and 80 sound-related verbs (mean number of letters = 6.89) comprising 28 sounds produced by animals (e.g., мычать, mychat', *to moo*), 20 sounds produced by inanimate object (e.g., звякать, zvyakat', *to tinkle*), and 32 human-made sounds (e.g. чихать, chikhat', *to sneeze*). In order to diminish the length of the questionnaire, the stimulus set was pseudo-randomly equally split into four lists: each list included 40 verbs and was randomly assigned to 35 participants.

ii) Manual checking of grammatical (i.e., transitivity), lexical (i.e., word length, frequency) and semantic (i.e., instrumentality, frequency) properties. Transitivity was checked with a Russian language dictionary (Efremova, 2000). Word length in graphemes was checked manually. Instrumentality ratings were obtained by using the StimulStat database (Alexeeva, Slioussar, & Chernova, 2018). In the few instances when a verb was not included in the database, ratings were obtained by two linguists who rated the items individually and independently. Word frequency was checked using the frequency dictionary of Russian vocabulary (Lyashevskaya & Sharov, 2009).

Table 2. Matching Mean Scores of Conceptual and Psycholinguistic Stimulus Features Within List A

	Acoustic	Emotion	Visual	Motor	Familiarity	Word Length, graphemes	Word Frequency, ipm
Sound verbs	4.77	3.26	3.32	2.57	4.63	7.08	24.25
Action verbs	2.38	2.31	4.14	4.30	4.65	6.92	26.15
Sound vs. Action verbs (*p*-values of two-tailed *t*-tests)	< .01	< .01	< .01	< .01	.77	.65	.88

Note. Psycholinguistic properties were rated on a five-point Likert scale (one = low familiarity/relevance; five = high familiarity/relevance).

Table 3. Matching Mean Scores of Conceptual and Psycholinguistic Stimulus Features Within List B

	Acoustic	Emotion	Visual	Motor	Familiarity	Word Length, graphemes	Word Frequency, ipm
Sound verbs	4.70	3.10	3.71	2.71	4.59	6.79	79.72
Action verbs	2.59	2.43	4.25	4.37	4.65	6.83	35.7
Sound vs. Action verbs (*p*-values of two-tailed *t*-tests)	< .01	< .01	< .01	< .01	.28	.92	.55

Note. Psycholinguistic properties were rated on a five-point Likert scale (one = low familiarity/relevance; five = high familiarity/relevance).

Table 4. Matching Mean Scores of Conceptual and Psycholinguistic Stimulus Features Between Lists

	Acoustic	Emotion	Visual	Motor	Familiarity	Word Length, graphemes	Word Frequency, ipm
Verbs List A	3.58	2.79	3.73	3.44	4.64	7	25.2
Verbs List B	3.64	2.76	3.98	3.54	4.62	6.81	57.71
Verbs List A vs. Verbs List B (*p*-values)	.79	.88	.03	.59	.56	.49	.38
Sound v. List A vs. Sound v. List B (*p*-values)	.25	.39	.02	.32			
Action v. List A vs. Sound v. List B (*p*-values)	.39	.43	.21	.30			

Note. *p*-values refer to the *p*-values of two-tailed *t*-tests. Psycholinguistic properties were rated on a five-point Likert scale (one = low familiarity/relevance; five = high familiarity/relevance).

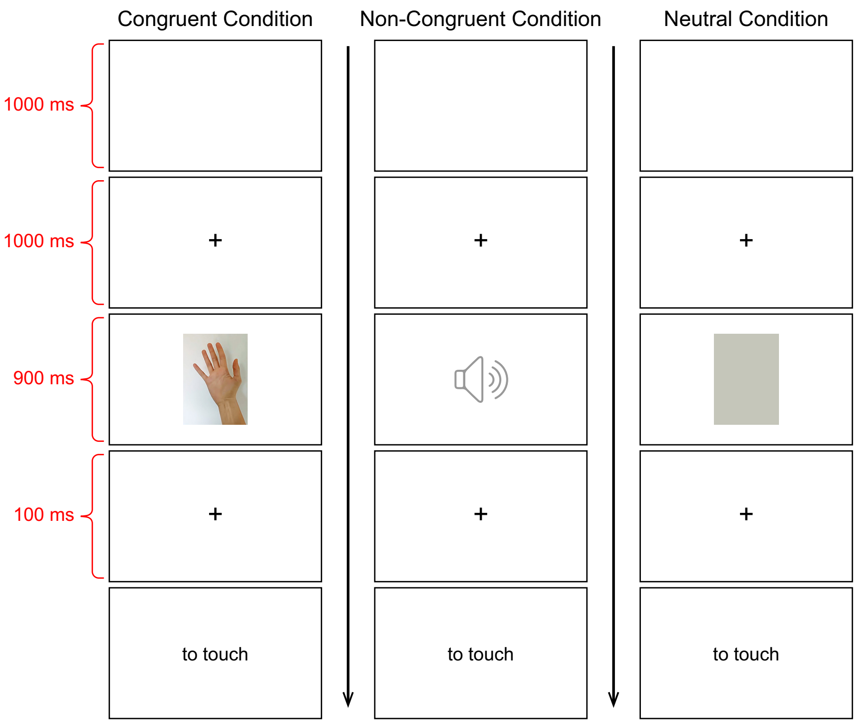

Figure 4. Trial presentation structure: a blank screen for 1000 ms, a fixation cross for 1000 ms, followed by a prime for 900 ms. Then a fixation cross appears only for 100 ms, followed by the target verb (or pseudoverb). In this figure, three conditions are presented: congruent (in this case, the action verb "to touch" preceded by the hand video clip), non-congruent (here, an action verb preceded by the bike bell sound, represented by an audio icon for demonstration purposes only) and neutral (here, an action verb preceded by a static video clip). All materials are in Russian. To see the live experimental paradigm, click here: https://youtu.be/9NviqvLdbPA

After that, to create the stimulus list for the ensuing priming experiment, verbs were selected that were included in the survey and in the manual ratings had a rating of four or five for action or sound features. However, multidimensional verbs, which are verbs having a high rating (>4.5 on a 5-point Likert scale) for any other feature (except familiarity), were excluded.

Then, two final lists were created (List A and B, see Appendix A), each one having verbs of three types (96 verbs in total). List A was composed of 24 action verbs (4 actions made by a tool such as *to paint*, 14 made by a hand such as *to push*, 6 made by both such as *to wash*), 24 sound verbs (6 sounds produced by animals such as *to woof*, 4 made by an inanimate object such as *to creak*, 14 made by humans such as *to call*), and 48 pseudoverbs. List B was composed of 24 action verbs (8 actions made by a tool such as *to paddle*, 11 made by a hand such as *to touch*, 5 by both such as *to smear*), 24 sound verbs (10 sounds produced by animals such as *to roar*, 7 made by an inanimate object such as *to click*, 7 made by humans such as *to sneeze*), and 48 pseudoverbs. Action and sound verbs were not matched for transitivity and instrumentality features (see Table 1).

Action and sound verbs were matched for familiarity, word length, and word frequency within list A (see Table 2) and within list B (see Table 3).

Verbs of list A and verbs of list B were matched for most of the above-mentioned conceptual and psycholinguistic features. The visual feature was not perfectly matched between lists. However, this difference was not due to differences in the action verbs, where the visual component has a high relevance in action performance, but between the sound verbs of list A and sound verbs of list B (see Table 4).

Finally, we created three different primes: (1) a video clip of a moving right hand, (2) a sound produced by a bike bell, and (3) a static video clip including only the background of the first prime. All primes had a duration of 900 ms. In addition, primes (1) and (3) shared the same dimensions (width = 608 px, height = 858 px) and were always presented as silent video primes. Prime (3) was included as a neutral baseline condition to determine whether any effect on hand-related action verbs was due to the prime (1) or to the hand responses (Klepp et al., 2019; Carreiras et al., 2007). In each list, for each verb category (i.e., action verbs, pseudoverbs, sound verbs), 8 targets were preceded by prime (1), 8 targets by prime (2), and 8 targets by prime (3). Between lists, verbs belonging to the same verb category and preceded by the same prime were matched for the critical feature (i.e., acoustic for sound verbs, motor for action verbs), familiarity, word length, and word frequency.

Design and Conditions

Each trial was comprised of: (a) a blank screen for 1000 ms, (b) a fixation cross (+) appearing for 1000 ms, (c) a prime for 900 ms; (d) a fixation cross (+) for 100 ms; and (e) a target word displayed by the participant's answer (see Figure 4). The structure of the trials, including the stimulus presentation times and inter-stimulus intervals, was based on Murteira et al. (2019).

Visual elements (i.e., fixation crosses and video clips) were placed in full width screen layout (100 %) and centered in the middle of the screen. The target stimuli were placed in the default screen layout given with the text content.

The experiment had three conditions:

- A *congruent condition* where the prime and target are matched (e.g., hand video clip preceding an action verb, or bike bell sound preceding a sound verb);
- A *non-congruent condition* where the prime and target are not matched (e.g., hand video clip preceding a sound verb, or bike bell sound preceding an action verb); and
- A *neutral condition* where the prime, which is completely meaningless, cannot have any potential influence on any target (e.g., static video clip preceding an action verb, or static video clip preceding a sound verb).

Procedure

The experiment was conducted online. The Gorilla Experiment Builder (www.gorilla.sc) was used to create and host the experiment (Anwyl-Irvine, Massonnié, Flitton, Kirkham, & Evershed, 2018). Data were collected between 27-05-2020 and 08-06-2020.

In order to avoid distractions, participants were asked to find a quiet place where they would not be disturbed, to wear their headphones, and to place their mobile communication devices behind the computer (or somewhere out of their view). Before starting the task, individuals had to complete a questionnaire about their education level, primary occupation, and handedness using the short form of the Edinburgh Handedness Inventory (Veale, 2014).

Participants were instructed that first, they would watch a brief video clip, or they would hear a sound, and that no response was needed. Participants were then instructed to respond, as fast and as accurately as possible, to the second stimulus (i.e., the written word), deciding whether the word shown is a real word, by pressing "←" on their keyboard, and otherwise pressing "→". A practice round of six items was included to avoid technical issues. The same practice session preceded list A and list B. A complete online session took around 15 minutes.

Data Analysis

The data analysis was conducted with RStudio (RStudio Team, 2020). The primary dependent variables of interest were *accuracy* and *reaction time* (*RT*) for correct answers, and these were separately analyzed using the *lme4* package (Bates et al., 2015). *Accuracy* had a binary classification with a score of 1 for the correct answer and 0 for an incorrect answer. *RT* was defined as the time in milliseconds that elapsed between the onset of the target word and the response (i.e., button press). They were both scored automatically by the Gorilla Experiment Builder. The independent variables were *verb type* (action verbs vs. pseudoverbs vs. sound verbs) and *prime type* (motor prime vs. neutral prime vs. auditory prime). Other independent variables were included only if they would have improved the model: *list* (A vs. B), *gender* (female vs. male vs. other), *handedness* (left-handed vs. mixed-handed vs. right-handed), *video games* (whether participant plays vs. does not play video games). Because *gender, handedness* and *video games* have less than five levels each, they were treated as fixed effects (Harrison et al., 2018). Finally, *participants* and *items* were included as random effects in the overall model estimation. Because every participant was exposed to different stimuli (list A and list B), *participants* and *items* were not treated as crossed effects.

For *accuracy*, generalized linear mixed models were constructed using the *glmer* function in order to measure the effect of *prime type, verb type,* and their interaction. The models were fit using a Laplacian approximation to the log-likelihood. A binomial distribution was chosen to match the properties of measured accuracy. Four different models were compared using ANOVA, all with the same random effects specification:

- M0: Accuracy ~ (1 | Participant) + (1 | Item)
- M1: Accuracy ~ List + Gender + Handedness + Video games + (1 | Participant) + (1 | Item)
- M2: Accuracy ~ Prime type × Verb type + (1 | Participant) + (1 | Item)
- M3: Accuracy ~ Prime type × Verb type + List + Gender + Handedness + Games + (1 | Participant) + (1 | Item)

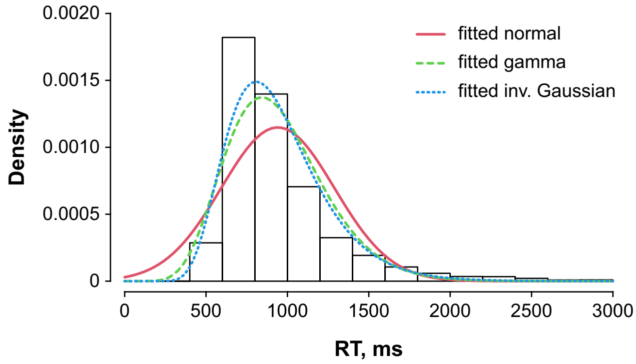

Figure 5. Observed and fitted densities to RT. Bars represent the observed densities to RT, while lines show the fitted densities

The resulting model with a significant *p*-value as well as the lowest Akaike Information Criterion (AIC) was further analyzed.

Moreover, *accuracy* related to real verbs (i.e., excluding pseudoverbs) was further explored by introducing *transitivity* (transitive vs. optional vs. intransitive), *hand action strength* (i.e., how strongly the concept is experienced by performing an action with the hand/arm; Lynott, Connell, Brysbaert, Brand, & Carney, 2019), and *instrumentality* (instrumental vs. optional vs. not instrumental) as fixed effects. These properties could act as potential confounds. Four different models were compared using ANOVA:

- M0: Accuracy ~ (1 | Participant) + (1 | Item)
- M1: Accuracy ~ Transitivity + (1 | Participant) + (1 | Item)
- M2: Accuracy ~ Transitivity × Hand action strength + (1 | Participant) + (1 | Item)
- M3: Accuracy ~ Transitivity × Hand action strength × Instrumentality + (1 | Participant) + (1 | Item)

Similarly to above, the model with a significant *p*-value and lowest AIC was examined.

Concerning RTs, as in most simple decision tasks, the distribution was positively skewed. In accordance with the example set of Lo and Andrews (2015), and due to the potential unreliability and uninformativity of back-transformation, the observed deviation from normality was not eliminated. Therefore, in order to perform a statistical assessment on these raw RT data, while meeting the assumptions of the statistical model, generalized mixed linear models were constructed using the *glmer* function. The Gamma and inverse Gaussian distributions, both characterized by a unimodal skewed distribution with continuous responses greater than or equal to 0, thus associated with RT measures (Lo & Andrews, 2015), were visually compared with our raw RT data (see Figure 5).

The Inverse Gaussian distribution seemed to show a better fit to RT responses: it is the one that best approximates the surface characteristics of the distribution of the observed RT. Hence, in generalized linear mixed models, the Inverse Gaussian distribution was chosen to match the properties of the measured RT. The models were fit using a Laplacian approximation to the log-likelihood. Four different models were compared with the ANOVA, all with the same random effects specification:

- M0: RT ~ (1 | Participant) + (1 | Item)
- M1: RT ~ List + Gender + Handedness + Video games + (1 | Participant) + (1 | Item)
- M2: RT ~ Prime type × Verb type + (1 | Participant) + (1 | Item)
- M3: RT ~ Prime type × Verb type + List + Gender + Handedness + Games + (1 | Participant) + (1 | Item)

The model with a significant *p*-value as well as the lowest Akaike Information Criterion (AIC) was further analyzed.

Furthermore, RTs limited to real verbs were inspected with specific fixed effects: *transitivity, hand action strength*, and *instrumentality*. Four models were compared using ANOVA:

- M0: RT ~ (1 | Participant) + (1 | Item)
- M1: RT ~ Transitivity + (1 | Participant) + (1 | Item)
- M2: RT ~ Transitivity × Hand action strength + (1 | Participant) + (1 | Item)
- M3: RT ~ Transitivity × Hand action strength × Instrumentality + (1 | Participant) + (1 | Item)

The one model that overcame the others by showing a significant *p*-value and the lowest AIC was analyzed.

Results

Accuracy and reaction time measures across 69 participants (i.e., 6 were excluded) and across 192 stimulus items (48 action verbs, 96 pseudoverbs, 48 sound verbs) were collected and analyzed. Overall, data having physically impossibly short RTs (button presses within 200 ms of stimulus onset) and very long response latencies (exceeding 3 seconds) were excluded (Balota et al., 2007): 108 out of 6,624 (1.63 %) data points were excluded from the data analysis of both accuracy and RTs.

Accuracy Data

Overall accuracy was 96.32 % (correct: 6,340; incorrect: 176). Following model comparisons, arising from the maximum likelihood ratio test using an ANOVA, the most representative model (M2; for a summary, see Table 5) carried an AIC value of 1,437.5, with log-likelihoods represented in a chi-square statistic, $X^2(2) = 10.89$, $p = .004$. No significant interaction emerged between prime type and verb type in the overall model. Furthermore, the model showed a significant *p*-value for the accuracy related to pseudoverbs, with an estimate of −1.73 ($p = .031$), and to sound verbs, with an estimate of −2.16 ($p = .012$). Responses to action verbs (accuracy = 98.97 %; *SD* = 2.57) were significantly more accurate compared to pseudoverbs (accuracy = 96.89 %; *SD* = 6.70) and to sound verbs (accuracy = 96.16 %; *SD* = 6.05). No difference in accuracy appeared between pseudoverbs and sound verbs. Summaries of accuracy measures are reported in Figure 6.

With the aim of exploring the pattern behind the difference in accuracy across real verbs specifically, a new group of models were compared: the most representative model, M1 (for a summary, see Table 6), carried an AIC value of 573.5, with log-likelihoods represented in a chi-square statistic, $X^2(2) = 15.67$, $p < .001$.

In detail, the model showed a significant *p*-value for the accuracy related to (1) verbs that can be both transitive and intransitive (i.e., optional), with an estimate of 2.02 ($p < .001$); and (2) transitive verbs, with an estimate of 1.55 ($p < .01$). Responses to intransitive verbs (accuracy = 95.36 %; correct = 843; incorrect = 41) were significantly less accurate than responses to verbs that can be transitive or intransitive (accuracy = 99.05 %; correct = 1352; incorrect = 13). Responses to intransitive verbs were significantly less accurate than responses to transitive verbs (accuracy = 98.54 %; correct = 810; incorrect = 12). Responses to verbs that can be both transitive and intransitive did not significantly differ in accuracy compared to transitive verbs.

Taken together, the difference between action and sound verbs cannot be explained by differences in instrumentality or hand action strength, but by transitivity alone. Indeed, responses to intransitive verbs, all of which are sound verbs, were performed less accurately than both optional transitive verbs (both action and sound verbs) and transitive verbs (mainly action verbs). The intransitive verbs (*N* = 28) included in the study were all sound verbs, evenly divided between unaccusative (i.e., with a patient-like subject; e.g., тикать, tikat', *to tick*; *n* = 15) and unergative (i.e., with agent-like subject; e.g., ахать, ahat›, *to gasp; n* = 13).

Reaction Time Data

First, an outlier identification procedure was adopted: outlier trimming (Balota et al., 2007) was performed using the *sdTrim* function in R. In this way, 4.28 % of trial data (*n* = 279) did not enter the analysis for RT. The distribution of obtained RTs remained positively skewed (see Figure 7).

Following model comparisons, arising from the maximum likelihood ratio test using an ANOVA, the most representative model, M2 (for a summary, see Table 7), carried an AIC value of 83536.5, with log-likelihoods represented in a chi-square statistic, $X^2(2) = 36.93$, $p < .001$.

No significant interaction emerged between prime type and verb type in the overall model. Moreover, the RT related to action and sound verbs was significantly lower (with estimates of −120.44, $p < .001$ and −106.86, $p < .001$, respectively) than for pseudowords. The RT in the lexical decision task was higher for pseudoverbs (RT = 1022 ms; *SD* = 373) compared to both action verbs (RT = 869 ms; *SD* = 342) and sound verbs (RT = 897 ms; *SD* = 338), respectively. Summaries of RT measures by verb type are presented in Figure 8.

Secondly, models including RT to real verbs only as a dependent variable were compared with a maximum likelihood ratio test. No model was a significantly better fit to the data. That is, neither transitivity, hand action strength, or instrumentality played a role in RT responses to real verbs.

Discussion

This study investigated the embodiment of action and sound verbs. To do so, we assessed whether motor and auditory primes differentially influence the processing

Table 5 Summary Generalized Linear Mixed Model M2 for Accuracy

Model: M2 Accur ~ Prime type × Verb type + (1|Participant) + (1|Item)

AIC	BIC	log Lik	deviance	*df* resid.
1437.4	1512.0	–707.71	1415.4	6505

Scaled Residuals:

Min	1Q	Median	3Q	Max
–10.92	0.07	0.09	0.15	1.05

Random Effects:

Groups	Name	Variance	*SD*
Item	(Intercept)	1.98	1.41
Participant	(Intercept)	0.38	0.62

Fixed Effects:	Estimate	Std. Error	*z* value	Pr (>|*z*|)
(intercept)	6.18	0.75	8.29	<2e–16 ***
Motor prime	0.27	1.07	0.25	.800
Neutral prime	–1.22	0.90	–1.36	.173
Pseudoverb	–1.73	0.80	–2.16	.031 *
Sound verb	–2.16	0.86	–2.53	.012 *
Motor prime: Pseudoverb	–0.35	1.17	–0.30	.767
Neutral prime: Pseudoverb	1.51	1.03	1.47	.141
Motor prime: Sound verb	0.50	1.27	0.39	.694
Neutral prime: Sound verb	1.12	1.10	1.01	.312

Note. Number of observations: 6516. Number of items: 192. Number of participants: 69. The reference level for Verb type is action verb and for Prime type is auditory prime. *** $p < .001$; * $p < .05$.

Table 6 Summary Generalized Linear Mixed Model M1 for Accuracy in Verbs

Model: M1 Accur ~ Transitivity + Verb type + (1|Participant) + (1|Item)

AIC	BIC	log Lik	deviance	*df* resid.
573.5	603.7	–281.8	563.5	3066

Scaled Residuals:

Min	1Q	Median	3Q	Max
–8.52	0.04	0.07	0.12	1.84

Random Effects:

Groups	Name	Variance	*SD*
Item	(Intercept)	1.97	1.40
Participant	(Intercept)	0.90	0.95

Fixed Effects:	Estimate	Std. Error	*z* value	Pr (>|*z*|)
(Intercept)	3.99	0.42	9.45	<2e–16***
Transitivity “can be both”	2.02	0.56	3.61	.000309 ***
Transitivity “transitive”	1.55	0.60	2.60	.009560 **

Note. Number of observations: 3071. Number of items: 90. Number of participants: 69. The reference level for Transitivity is “intransitive”. *** $p < .001$; ** $p < .01$.

Table 7 **Summary Generalized Linear Mixed Model M2 for Reaction Time**

Model: M2	RT ~ Prime type × Verb type + (1 | Participant) + (1 | Item)			
AIC	BIC	log Lik	deviance	*df* resid.
83536.5	83617.3	−41756.2	83512.5	6225

Scaled Residuals:

Min	1Q	Median	3Q	Max
−1.98	−0.65	−0.23	0.39	7.58

Random Effects:

Groups	Name	Variance	*SD*
Item	(Intercept)	2.972e+03	5.451e+01
Participant	(Intercept)	1.066e+04	1.033e+02
Residual		6.516e-05	8.072e–03

Fixed Effects:	Estimate	Std. Error	*z* value	Pr (>|*z*|)
(intercept)	1195.62	17.43	68.59	<2e–16 ***
Neutral prime	8.14	17.11	0.48	.63
Auditory prime	−3.23	17.07	−0.19	.85
Action verb	−120.44	19.89	−6.06	1.39e–09 ***
Sound verb	−106.86	20.01	−5.34	9.31e–08 ***
Neutral prime : Action verb	33.97	28.35	1.20	.23
Auditory prime : Action verb	−12.69	28.00	−0.45	.65
Neutral prime : Sound verb	12.10	28.46	0.43	.67
Auditory prime : Sound verb	29.75	28.43	1.05	.30

Note. Number of observations: 6237. Number of items: 192. Number of participants: 69. The reference level for Verb type is pseudoverb and for Prime type is motor prime. *** $p < .001$.

of hand-related action verbs (e.g., *to push*) and sound verbs (e.g., *to buzz) in* cross-modal feature repetition priming. In order to determine facilitation and/or inhibition effects, the experiment included three test conditions comprising congruent prime-target pairs (i.e., motor prime followed by an action verb; auditory prime followed by a sound verb), incongruent prime-target pairs (i.e., motor prime followed by a sound verb; auditory prime followed by an action verb), and a control condition where verbs were preceded by a neutral prime (i.e., a static video clip including only the background of the motor prime). Reaction time and accuracy were obtained and analyzed to identify potential similarities and differences in action and sound verb processing preceded by a certain prime. Overall, the task was performed with high accuracy (96.32 %).

The first hypothesis stated that the previous observation of an unspecified hand movement (i.e., motor prime) would affect the processing of action-related verbs but not sound-related verbs by influencing accuracy and reaction times in a lexical decision task. In the second hypothesis, we indicated that the previous listening to a bike bell sound (i.e., auditory prime) would affect the processing of sound-related verbs but not action-related verbs by influencing accuracy and reaction times in a lexical decision task. Two generalized linear mixed models, one for accuracy and another one for RT, were adopted to evaluate the above hypotheses. The two models did not show any significant difference related to the interaction between the motor prime and action verbs, compared to the one between the motor prime and sound verbs (first research question), nor related to the interaction between the auditory prime and sound verbs, compared to the one between the auditory prime and action verbs (second research question).

Even though the findings did not match our predictions and hypotheses, two additional results must be taken into account: (1) Overall accuracy was significantly lower for intransitive verbs compared to both transitive and optional-transitive verbs; and (2) Pseudoverbs had a significantly longer response time compared to real verbs, and, in comparison to action verbs, lower accuracy. While (2) is in line with previous studies (e.g., Carreiras et al., 2007) and might be due to the lexicality effect (i.e., pseudowords are classified more slowly than words), (1) is peculiar because previous studies have shown that verbs with a higher number of arguments are more difficult to process (Thompson et al., 1997; Barbieri et al., 2015), as predicted by the *argument structure complexity* hypothesis (Thompson, 2003). Instead, our results support the *facilitation through complexity* hypothesis (Malyutina & den Ouden, 2017), which assumes that the argument structure of verbs has different effects on different tasks: argument complexity enables a better behavioral performance, as well as less wide neural recruitment, in a single-word lexical decision task; meanwhile, it results in poorer behavioral performance and more extensive neural recruitment in a sentence-level

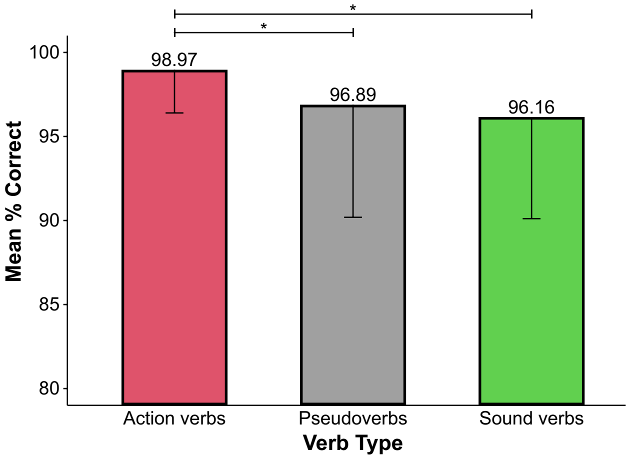

Figure 6. Mean percentage of correct answers by verb types.
* indicates a significant difference (*p* <.05).

judgement task. This is because, on the one hand, a linguistically complex verb argument structure provides more routes of verb access, rendering lexical access simpler; and, on the other hand, the facilitatory lexical effect prevails by additional morphosyntactic demands at the sentence level. The facilitation through complexity hypothesis may explain why, in the current lexical decision task, responses to intransitive verbs were performed less accurately than to transitive and optional-transitive verbs.

In the following sections, accuracy and RTs of the two verb categories will be discussed.

Priming Action and Sound Verbs

Our experiment tested whether pre-activating verbs with a motor and auditory prime differently modulates the processing of hand-related action vs. sound verbs within a lexical decision task. The generalized linear mixed models chosen to test accuracy and reaction time, respectively, did not show any difference between action and sound verbs preceded by the motor or auditory primes. The lack of support for our hypothesis (i.e., the previous exposure to a motor and auditory prime would affect the processing of action-related verbs and sound-related verbs, respectively, by making accuracy higher/lower and reaction times faster/slower), could have two possible interpretations, which are not mutually exclusive.

First, activation of the motor or auditory cortex, which was assumed to happen after seeing the motor or auditory prime respectively, does not influence the processing of action or sound verbs. In other words, the motor cortex does not contribute to the processing of motor-related verbs, nor does the auditory cortex contribute to the processing of sound-related verbs. That is because, in contrast with embodied cognition theories, concepts are represented in the brain in a common, and therefore amodal, format (e.g., Mahon & Caramazza, 2008).

The second possibility is that the lexical decision task evokes the processing of verbs at the pre-semantic level, while sensorimotor activation occurs only after the concept has been accessed (as a consequence of semantic elaboration). This implies that category-specific effects for action- and sound-related verbs are not detectable in the current implicit task, as this task taxes the input lexicon more than the semantic system (Popp, Trumpp, & Kiefer, 2019). Moreover, even if specific types of action verbs (i.e., hand-related action verbs) were selected as stimuli for the current study, our findings remain in line with those by Popp and colleagues (Popp, Trumpp, & Kiefer, 2019). Additional confirmation was provided by further exploring whether hand action strength, defined as how strongly the concept is experienced by performing an action with the hand/arm, could enter as a predictor for accuracy and/or RT responses to action and sound verbs. Indeed, that was not the case. Importantly, the current evidence is not compatible with the somatotopic activation of the motor system when processing action words (Hauk et al., 2004; Tettamanti et al., 2005), and it does not embrace any motor cortex contribution in action verb processing. It also does not support the definition of action words as semantic links binding language and action (Pulvermüller et al., 2005).

However, the current design does not allow us to opt for one interpretation: due to the behavioral nature of the study, we cannot argue for a specific degree of separation between perception/action and cognition. Future studies may investigate this design in the context of transcranial magnetic stimulation (TMS), commonly used for a theoretical understanding of the neural basis of language within a healthy population, and direct electrical stimulation (DES), a technique used to localize language functions in the brains of people with brain tumors and/or epilepsy (Rofes & Mahon, 2021). Specifically, TMS or DES might clarify the causal link between semantics and sensory-motor systems: by inhibiting specific motor and auditory areas, it will be possible to test the relevance of those in motor and auditory concepts. A better understanding

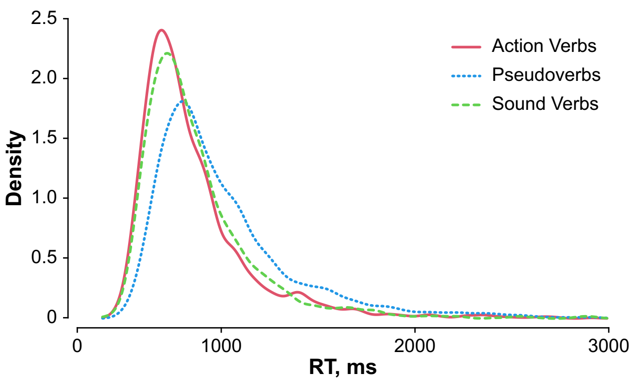

Figure 7. Kernel density estimation of RT measures by verb types

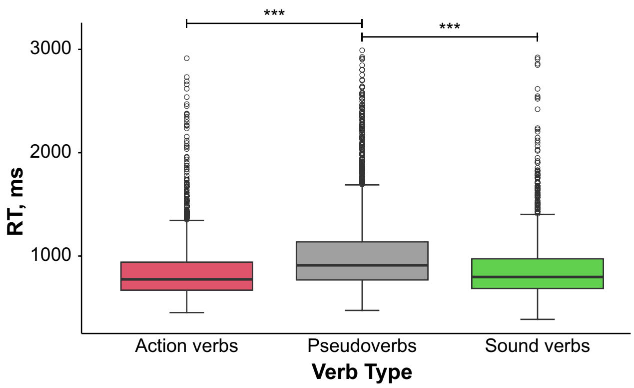

Figure 8. RTs measures by verb type.
*** indicates a significant difference (*p* < .001).

of the neural correlates of concepts within verbs provides not only a theoretical but also a clinical contribution: it will enable more accurate preoperative, as well as intraoperative, language mapping.

Limitations and Future Directions

The current study explored the use of cross-modal priming in evaluating embodied cognition within verbs. The fact that different primes did not affect the processing of different verbs in a lexical decision task might raise the question of whether any priming occurred during the presentation of these stimuli. Thus, while the promising findings need replication, the design must be adjusted. Action and sound verbs will be separately analyzed below.

First of all, due to the difference in transitivity between action and sound verbs, and having known that transitivity plays a significant role in the lexical access, future studies may include another category of action verbs, such as foot-related action verbs, having comparable grammatical and conceptual features (e.g., transitivity and instrumentality). Moreover, the motor prime was built on the assumption that the activation of mirror neurons is largely automatic and is achieved without any high level mental processes (Rizzolatti & Sinigaglia, 2010). In other words, the observation of a moving hand should easily and quickly activate those brain areas required to perform the same action (i.e., dorsolateral sites of the motor strip). However, their potential activation during an action observation makes their representations not exclusively motor but also visual (Caramazza et al., 2014), and therefore motor and visual signals might have interfered with each other. Furthermore, it might be argued that an active hand action is required to engage the motor system. In the current experiment, the hand response effector was implicitly involved: participants were instructed to make a lexical decision by pressing the keyboard buttons "←" or "→" with the right hand. It has been shown that in this type of task there is an increased activation of the regions associated with finger press responses (Carreiras et al., 2007). Hence, the results would have indicated a somatotopic verb-motor priming effect; that is, responses to action verbs would have been facilitated because they were performed with the effector (in this case, the hand) described by a verb (in this case, hand-related action verbs). However, that was not the case.

Second, concerning the auditory prime, it has been revealed that the cortical network is category-organized for sound processing. Since previous studies have shown a category-preferential organization for processing real-world sounds (i.e., human, animal, mechanical, environmental sound sources; Engel et al., 2009; Lemaitre et al., 2018), it is possible that supplying a mechanical sound as the prime for all sound verbs, without taking into consideration whether the verb denoted a human-made, animal, or inanimate-object sound, did not generate any specific activation/facilitation. For instance, the auditory prime (i.e., bike bell sound) and the animal-related sound verb (e.g., *to moo*), might have activated different cortical networks: the mechanical sound would lead to a preferential activation of areas associated with processing the visual features or form of an object (e.g., left parahippocampal cortex; Engel et al., 2009); whereas animal sounds would activate motor-related regions (i.e., bilateral anterior and posterior/middle insular cortices; Engel et al., 2009). Therefore, future studies may include three different primes, one for each category of sound verb, such as a dog barking for animal sounds, someone singing for human sounds, and a bike bell sound for mechanical sounds. Then, the comparison will happen between different verb categories preceded by the same prime. There should be a priming effect when the prime belongs to the same category of the following target verb. Alternatively, in order to further investigate the role of the auditory cortex in the processing of sound verbs, future studies might include both action and sound verbs, presenting half of them in the auditory modality and the other half in the visual modality. According to embodied cognition theories (Barsalou, 1999), there should be a priming effect (i.e., facilitation or inhibition) when sound verbs, compared to action verbs, are presented in the auditory modality. Taken together, future studies may ascertain the efficacy of visual-motor and auditory primes to elicit a general response of the motor or auditory cortex, respectively, on a neurological basis (e.g., fMRI or EEG).

Finally, three stimulus lists should be prepared (one list per condition), each of them containing the same items appearing with different primes. Also, for hand-related action verbs, the somatotopic verb-motor priming effect should be properly assessed by setting a response time limit. This is because a time constraint sets equal conditions for all participants and gives more precise timing.

Conclusion

This study is a first step towards integrating three lines of research: cross-modal priming, different verb categories, and embodied cognition theories, that, to our knowledge, have not been directly linked. Although the results call for replication, the present research contributes to a growing body of evidence regarding embodied cognition at the lexical level. We hope that it will stimulate further investigation in this exciting field of research.

References

Alexeeva, S., Slioussar, N., & Chernova, D. (2018). StimulStat: A lexical database for Russian. *Behavior Research Methods, 50*(6), 2305–2315. https://doi.org/10.3758/s13428-017-0994-3

Anwyl-Irvine, A.L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J.K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behavior Research Methods, 52*(1), 388–407. https://doi.org/10.3758/s13428-019-01237-x

Balota, D.A., Yap, M.J., Hutchison, K.A., Cortese, M.J., Kessler, B., Loftis, B., Neely, J.H., Nelson, D.L., Simpson, G.B., & Treiman, R. (2007). The English lexicon project. *Behavior Research Methods, 39*(3), 445–459. https://doi.org/10.3758/bf03193014

Barbieri, E., Aggujaro, S., Molteni, F., & Luzzatti, C. (2015). Does argument structure complexity affect reading? A case study of an Italian agrammatic patient with deep dyslexia. *Applied Psycholinguistics, 36*(3), 533–558. https://doi.org/10.1017/s0142716413000337

Barsalou, L.W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*(4), 577–660. https://doi.org/10.1017/s0140525x99002149

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statis-*

tical Software, 67(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Buccino, G., Colagè, I., Silipo, F., & D'Ambrosio, P. (2019). The concreteness of abstract language: An ancient issue and a new perspective. *Brain Structure and Function, 224*, 1385–1401. https://doi.org/10.1007/s00429-019-01851-7

Caramazza, A., Anzellotti, S., Strnad, L., & Lingnau, A. (2014). Embodied cognition and mirror neurons: A critical assessment. *Annual Review of Neuroscience, 37*(1), 1–15. https://doi.org/10.1146/annurev-neuro-071013-013950

Carreiras, M., Mechelli, A., Estévez, A., & Price, C.J. (2007). Brain activation for lexical decision and reading aloud: Two sides of the same coin? *Journal of Cognitive Neuroscience, 19*(3), 433–444. https://doi.org/10.1162/jocn.2007.19.3.433

Efremova, T.F. (2000). *New explanatory dictionary of Russian word derivations. [Novyy slovar russkogo yazyka. Tolkovo-slovoobrazovatelnyy], Vol. 2.* Moscow: Russkiy Yazyk. (In Russian).

Engel, L.R., Frum, C., Puce, A., Walker, N.A., & Lewis, J.W. (2009). Different categories of living and non-living sound-sources activate distinct cortical networks. *NeuroImage, 47*(4), 1778–1791. https://doi.org/10.1016/j.neuroimage.2009.05.041

García, A.M., & Ibáñez, A. (2016). A touch with words: Dynamic synergies between manual actions and language. *Neuroscience & Biobehavioral Reviews, 68*, 59–95. https://doi.org/10.1016/j.neubiorev.2016.04.022

Harrison, X.A., Donaldson, L., Correa-Cano, M.E., Evans, J., Fisher, D.N., Goodwin, C.E.D., Robinson, B.S., Hodgson, D.J., & Inger, R. (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ, 6*, e4794:1–32. https://doi.org/10.7717/peerj.4794

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*(2), 301–307. https://doi.org/10.1016/s0896-6273(03)00838-9

Keuleers, E., & Brysbaert, M. (2010). Wuggy: A multilingual pseudoword generator. *Behavior Research Methods, 42*(3), 627–633. https://doi.org/10.3758/brm.42.3.627

Kiefer, M., Sim, E.-J., Herrnberger, B., Grothe, J., & Hoenig, K. (2008). The sound of concepts: Four markers for a link between auditory and conceptual brain systems. *Journal of Neuroscience, 28*(47), 12224–12230. https://doi.org/10.1523/jneurosci.3579-08.2008

Klepp, A., van Dijk, H., Niccolai, V., Schnitzler, A., & Biermann-Ruben, K. (2019). Action verb processing specifically modulates motor behaviour and sensorimotor neuronal oscillations. *Scientific Reports, 9*(1), 15985:1–11. https://doi.org/10.1038/s41598-019-52426-9

Kousta, S.-T., Vinson, D.P., & Vigliocco, G. (2009). Emotion words, regardless of polarity, have a processing advantage over neutral words. *Cognition, 112*(3), 473–481. https://doi.org/10.1016/j.cognition.2009.06.007

Lemaitre, G., Pyles, J.A., Halpern, A.R., Navolio, N., Lehet, M., & Heller, L.M. (2018). Who's that knocking at my door? Neural bases of sound source identification. *Cerebral Cortex, 28*(3), 805–818. https://doi.org/10.1093/cercor/bhw397

Lo, S., & Andrews, S. (2015). To transform or not to transform: Using generalized linear mixed models to analyse reaction time data. *Frontiers in Psychology, 6*, 1171:1–16. https://doi.org/10.3389/fpsyg.2015.01171

Lyashevskaya, O., & Sharov, S. (2009). *The frequency dictionary of modern Russian language based on Russian National Corpus.* Moscow: Azbukovnik. (In Russian).

Lynott, D., Connell, L., Brysbaert, M., Brand, J., & Carney, J. (2019). The Lancaster Sensorimotor Norms: Multidimensional measures of perceptual and action strength for 40,000 English words. *Behavior Research Methods, 52*(3), 1271–1291. https://doi.org/10.3758/s13428-019-01316-z

Mahon, B.Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris, 102*(1--3), 59–70. https://doi.org/10.1016/j.jphysparis.2008.03.004

Malyutina, S., & den Ouden, D.-B. (2017). Task-dependent neural and behavioral effects of verb argument structure features. *Brain and Language, 168*, 57–72. https://doi.org/10.1016/j.bandl.2017.01.006

Mirabella, G., Iaconelli, S., Spadacenta, S., Federico, P., & Gallese, V. (2012). Processing of hand-related verbs specifically affects the planning and execution of arm reaching movements. *PLoS ONE, 7*(4), e35403:1–14. https://doi.org/10.1371/journal.pone.0035403

Murteira, A., Sowman, P.F., & Nickels, L. (2019). Taking action in hand: Effects of gesture observation on action verb naming. *Language, Cognition and Neuroscience, 34*(3), 351–364. https://doi.org/10.1080/23273798.2018.1552978

Paivio, A., Yuille, J.C., & Madigan, S.A. (1968). Concreteness, imagery, and meaningfulness values for 925 nouns. *Journal of Experimental Psychology, 76*(1, Pt.2), 1–25. https://doi.org/10.1037/h0025327

Popp, M., Trumpp, N.M., & Kiefer, M. (2016). Feature-specific event-related potential effects to action- and sound-related verbs during visual word recognition. *Frontiers in Human Neuroscience, 10*, 637:1–16. https://doi.org/10.3389/fnhum.2016.00637

Popp, M., Trumpp, N.M., & Kiefer, M. (2019). Processing of action and sound verbs in context: An fMRI study. *Translational Neuroscience, 10*(1), 200–222. https://doi.org/10.1515/tnsci-2019-0035

Popp, M., Trumpp, N.M., Sim, E.-J., & Kiefer, M. (2019). Brain activation during conceptual processing of action and sound verbs. *Advances in Cognitive Psychology, 15*(4), 236–255. https://doi.org/10.5709/acp-0272-4

Powers, K.L., Brooks, P.J., Aldrich, N.J., Palladino, M.A., & Alfieri, L. (2013). Effects of video-game play on information processing: A meta-analytic investigation. *Psychonomic Bulletin & Review, 20*(6), 1055–1079. https://doi.org/10.3758/s13423-013-0418-z

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience, 6*(7), 576–582. https://doi.org/10.1038/nrn1706

Pulvermüller, F., Hauk, O., Nikulin, V.V., & Ilmoniemi, R.J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience, 21*(3), 793–797. https://doi.org/10.1111/j.1460-9568.2005.03900.x

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations. *Nature Reviews Neuroscience, 11*(4), 264–274. https://doi.org/10.1038/nrn2805

Rofes, A., & Mahon, B.Z. (2021). Naming: Nouns and verbs. In E. Mandonnet, & G. Herbert (Eds.), *Intraoperative mapping of cognitive networks* (pp. 171–194). Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-030-75071-8_11

RStudio Team (2020). *RStudio: Integrated development environment for R.*Boston, MA: Retrieved from http://www.rstudio.com/.

Sato, M., Mengarelli, M., Riggio, L., Gallese, V., & Buccino, G. (2008). Task related modulation of the motor system during language processing. *Brain and Language, 105*(2), 83–90. https://doi.org/10.1016/j.bandl.2007.10.001

So, W.-C., Yi-Feng, A.L., Yap, D.-F., Kheng, E., & Yap, J.-M.M. (2013). Iconic gestures prime words: Comparison of priming effects when gestures are presented alone and when they are accompanying speech. *Frontiers in Psychology, 4*, 779:1–9. https://doi.org/10.3389/fpsyg.2013.00779

Tettamanti, M., Buccino, G., Saccuman, M.C., Gallese, V., Danna, M., Scifo, P., Fazio, F., Rizzolatti, G., Cappa, S.F., & Perani, D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of Cognitive Neuroscience, 17*(2), 273–281. https://doi.org/10.1162/0898929053124965

Thompson, C.K. (2003). Unaccusative verb production in agrammatic aphasia: The argument structure complexity hypothesis. *Journal of Neurolinguistics, 16*(2-3), 151–167. https://doi.org/10.1016/s0911-6044(02)00014-3

Thompson, C.K., Lange, K.L., Schneider, S.L., & Shapiro, L.P. (1997). Agrammatic and non-brain-damaged subjects' verb and verb argument structure production. *Apha-*

siology, 11(4-5), 473–490. https://doi.org/10.1080/02687039708248485

Veale, J.F. (2014). Edinburgh Handedness Inventory — Short Form: A revised version based on confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition, 19*(2), 164–177. https://doi.org/10.1080/1357650x.2013.783045

Yap, D.-F., So, W.-C., Melvin Yap, J.-M., Tan, Y.-Q., & Teoh, R.-L.S. (2011). Iconic gestures prime words. *Cognitive Science, 35*(1), 171–183. https://doi.org/10.1111/j.1551-6709.2010.01141.x

Appendix A: Experiment Lists

Verb Type	List	Stimuli	English Translations	Transitivity 0/1/2 for "is not X/ can be both/ is X"	Instrumentality 0/1/2 for "is not X/ can be both/ is X"	Psycholinguistic Properties (Mean Scores) acoustic	emotion	motor	visual	familiarity
Action verbs	**A**	мыть	to wash	2	2	2.94	2.60	4.34	4.46	4.94
		поднимать	to lift up	2	1	1.66	2.09	4.77	4.26	4.89
		затыкать	to plug	2	1	2.17	2.40	4.06	4.09	4.43
		втыкать	to stick	2	0	2.17	2.20	4.00	3.77	4.43
		открывать	to open	2	1	3.29	2.66	4.31	4.31	4.94
		катить	to roll	1	0	2.69	1.91	4.43	4.31	4.63
		толкать	to push	2	0	1.94	2.91	4.83	4.46	4.80
		забивать	to hammer	2	2	4.14	2.74	4.54	4.49	4.77
		месить	to knead	2	0	1.91	2.37	4.43	4.60	4.60
		хватать	to grab	1	0	1.46	2.23	4.57	4.00	4.43
		дергать	to pull (1)	1	0	1.97	2.89	4.49	3.94	4.77
		выбивать	to knock out	1	2	3.49	2.43	4.03	3.83	4.34
		ударять	to swipe up	1	1	3.80	3.26	4.03	3.06	4.71
		ставить	to put	2	0	1.89	1.46	4.09	3.77	4.69
		закрывать	to close	2	1	2.86	1.91	4.00	3.83	4.83
		косить	to mow	1	2	2.91	1.97	4.34	4.14	4.46
		сматывать	to wind up	2	0	1.91	2.06	4.60	3.97	4.37
		плести	to weave	1	0	1.43	2.11	4.03	3.97	4.46
		макать	to dunk	2	0	1.74	2.03	4.17	4.34	4.63
		лепить	to sculpt	1	0	1.49	2.11	4.14	4.29	4.69
		вешать	to hang	2	0	1.54	1.71	4.11	4.17	4.83
		колоть	to prick	1	2	2.86	2.20	4.23	4.23	4.54
		красить	to paint	1	2	1.49	2.23	4.23	4.80	4.80
		рвать	to tear	1	0	3.46	2.94	4.46	4.26	4.63
	B	вставлять	to paste	2	0	2.23	2.40	4.17	3.74	4.94
		душить	to strangle	2	1	2.86	3.97	4.23	4.37	4.69
		бросать	to throw	1	0	2.26	1.80	4.63	3.83	4.66
		накрывать	to cover	2	2	2.20	2.60	4.09	4.43	4.71
		бить	to beat	1	1	3.97	4.26	4.43	4.29	4.89
		чесать	to scratch	1	0	3.63	3.06	4.46	4.43	4.91
		трогать	to touch	1	0	1.74	3.09	4.49	4.23	4.89
		собирать	to assemble	2	0	1.77	2.37	4.20	4.06	4.83
		нести	to carry	1	0	1.80	2.46	4.20	3.91	4.74
		умывать	to wash	2	2	2.51	2.20	4.11	4.34	4.74
		тереть	to grate	2	2	3.69	1.89	4.77	4.31	4.71
		мазать	to smear	1	1	1.71	2.34	4.43	4.29	4.49
		брать	to take	1	0	1.37	1.89	4.40	4.09	4.66
		рубить	to chop	1	2	3.97	1.89	4.49	4.43	4.46
		ловить	to catch	2	1	1.86	1.97	4.34	3.91	4.43
		подметать	to sweep	2	2	3.51	1.83	4.51	4.31	4.51
		гнуть	to bend	1	0	2.20	2.34	4.49	4.49	4.80
		вырезать	to carve	2	2	3.11	2.43	4.26	4.43	4.83
		нажимать	to press	1	0	2.77	2.31	4.40	4.37	4.89
		строгать	to plane	2	2	3.49	2.40	4.23	4.40	4.37
		пожимать	to shake (hands)	1	0	1.91	2.31	4.26	4.23	4.40
		протыкать	to poke	2	1	2.66	2.29	4.11	4.23	4.23
		грести	to paddle	1	2	3.34	2.26	4.66	4.66	4.29
		тянуть	to pull (2)	1	1	1.60	2.03	4.49	4.14	4.51

Verb Type	List	Stimuli	English Translations	Transitivity 0/1/2 for "is not X/ can be both/ is X"	Instrumentality 0/1/2 for "is not X/ can be both/ is X"	Psycholinguistic Properties (Mean Scores)				
						acoustic	emotion	motor	visual	familiarity
Sound verbs	**A**	хрустеть	to crunch	0	0	4.71	2.00	2.40	2.71	4.71
		шептать	to whisper	1	0	4.80	3.14	2.83	3.74	4.89
		скрипеть	to creak	0	0	4.91	3.06	3.00	2.86	4.63
		грохотать	to rattle (1)	0	0	4.91	3.23	2.60	3.09	4.60
		квакать	to croak	1	0	4.91	2.74	2.49	3.86	4.60
		пыхтеть	to puff	0	0	4.46	3.40	2.89	3.43	4.46
		жужжать	to buzz	1	0	4.97	3.00	3.11	3.77	4.66
		кашлять	to cough	0	0	4.97	3.31	3.86	4.43	4.97
		каркать	to caw	0	0	4.94	3.03	2.71	3.97	4.69
		гнусавить	to twang	1	0	4.46	3.09	1.51	2.14	4.17
		петь	to sing	1	0	4.83	3.40	3.06	3.80	4.80
		храпеть	to snore	0	0	4.97	3.77	2.37	3.71	4.83
		тявкать	to yelp	0	0	4.77	3.57	2.60	3.77	4.60
		громыхать	to rumble	0	0	4.83	3.00	2.60	3.03	4.60
		визжать	to screech	1	0	4.91	4.46	2.71	3.69	4.66
		гоготать	to gag	0	0	4.49	4.00	2.57	3.40	4.29
		гавкать	to woof	0	0	4.97	3.69	3.23	4.20	4.80
		орать	to yell (2)	1	0	4.83	4.11	2.37	2.91	4.80
		звать	to call	2	0	4.23	2.74	2.11	2.54	4.83
		бубнить	to chant	1	0	4.60	3.03	1.87	2.40	4.40
		шикать	to boo	0	0	4.63	3.29	1.80	2.66	4.17
		кричать	to shout	1	0	4.74	4.06	2.46	3.37	4.80
		хрипеть	to wheeze	0	0	4.63	2.83	1.94	2.89	4.49
		свистеть	to whistle	0	1	4.94	2.37	2.54	3.40	4.77
	B	шелестеть	to rustle (1)	0	0	4.66	2.29	2.77	3.49	4.63
		мурлыкать	to purr	1	0	4.89	4.37	2.29	4.14	4.63
		чихать	to sneeze	0	0	4.86	2.57	3.66	4.40	4.77
		щелкать	to click	1	0	4.69	1.89	3.37	3.43	4.63
		лязгать	to clang	0	0	4.69	2.37	2.74	2.86	4.17
		говорить	to speak	1	0	4.37	2.77	3.26	4.00	4.86
		скулить	to whine	0	0	4.74	4.20	2.29	3.97	4.46
		выть	to howl	0	0	4.83	3.66	2.69	3.86	4.60
		щебетать	to twitter	0	0	4.74	3.29	2.03	3.77	4.43
		пищать	to squeak	0	0	4.77	3.43	2.29	2.74	4.83
		блеять	to bleat	0	0	4.83	2.83	2.11	3.89	4.46
		бормотать	to mumble	1	0	4.46	2.77	2.46	3.17	4.60
		вопить	to yell (1)	1	0	4.74	4.40	2.86	3.71	4.49
		ахать	to gasp	0	0	4.26	3.91	2.91	3.54	4.40
		сопеть	to sniff	0	0	4.51	2.69	2.66	3.26	4.63
		греметь	to rattle (2)	1	0	4.91	2.94	3.09	3.34	4.74
		журчать	to splatter	1	0	4.89	3.17	2.49	4.43	4.77
		шуршать	to rustle (2)	0	0	4.80	2.74	3.34	3.69	4.83
		реветь	to roar	0	0	4.69	4.34	3.20	4.34	4.74
		сипеть	to make hoarse sound	0	0	4.11	2.54	1.97	2.60	4.09
		рычать	to growl	1	0	4.80	3.66	3.17	4.11	4.80
		кудахтать	to cluck	1	0	4.80	2.71	2.69	4.11	4.57
		мычать	to moo	1	0	4.83	2.17	2.29	4.14	4.37
		тикать	to tick	0	0	4.91	2.60	2.46	4.09	4.57

Pseudoverbs	**A**	леть	дрибыть	лереть	жуждуть	танюкать
		сдарозать	фыдибить	мылоть	вибнуть	учигать
		удонзать	девеять	надбыть	хвякать	дойть
		фыкрыть	чистать	райть	нигнубать	незть
		мелькнать	зарживать	судрасть	гнять	ютолять
		касать	рылоть	вхомать	юревать	закать
		налкать	сматитать	фыдигать	знарыть	имивать
		вcленить	плеять	рвоцекать	хомеплать	двазить
		мешить	жутать	квещить	вогнить	мояхнуть
		хвачить	лесать	шаслыть		
	B	намыржать	телоть	заиспать	лелгать	градать
		чидать	расить	фехрскать	грать	цеснуть
		хвядать	сдеть	конуть	тклазать	маищить
		знакизать	тянить	тянить	щизить	мащить
		теть	кивить	шелелнеть	сбаить	лосить
		чесить	втрльнять	перлакать	слюборять	изойть
		тривать	крать	чипеть	жапать	жакоптать
		хлукрать	решицать	щелзать	пнять	рамить
		пайть	защуреть	гремять	укреть	ручать
		ощищить	унолгать	явлумать		

Note. The numbers after some verbs indicate that different verbs in Russian have the same translation in English. Transitivity was checked with a Russian language dictionary (Efremova, 2000). Instrumentality ratings were obtained by using the *StimulStat* database (Alexeeva, Slioussar, & Chernova, 2018). Psycholinguistic properties were rated on a five-point Likert scale (one = low familiarity/relevance; five = high familiarity/relevance).

экспериментальные сообщения

Моторный и звуковой прайминг глаголов действия и звучания в задаче лексического решения

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Аннотация. Согласно теориям воплощенного познания, понятия репрезентированы в сенсорных и моторных системах мозга. Эти репрезентации могут лежать в основе эффектов прайминга. Предположительно глаголы действия (например, «толкать») имеют более выраженные моторные ассоциации, а глаголы звучания (например, «жужжать») — слуховые. В работе рассматривается гипотеза, что моторный и звуковой прайминг имеют различный эффект на обработку глаголов действия и звучания в задании с лексическим решением. В эксперименте приняли участие 75 здоровых взрослых носителей русского языка. Им было предложено выполнить онлайн-задачу лексического решения с кросс-модальным праймингом. Участники смотрели фрагмент видео с движущейся рукой (моторный прайм), слышали звук велосипедного звонка (звуковой прайм) или видели нейтральный прайм. После этого они видели на экране глагол (действия, звучания или псевдослово) и должны были определить, является ли он существующим словом, нажав на соответствующую клавишу. Линейные модели со смешанными эффектами не выявили зависимости точности и скорости выполнения задания с глаголами обоих типов от вида прайма. Однако правильность ответа была ниже для непереходных, чем переходных / опционально переходных глаголов, вне зависимости от типа прайма. Кроме того, скорость ответа была ниже для псевдослов, чем для настоящих глаголов. Результаты не демонстрируют категориально-специфичных эффектов обработки глаголов действия и звука в задании с лексическим решением. Однако данные для непереходных глаголов поддерживают гипотезу «фасилитации сложностью», согласно которой глаголы с более сложной аргументной структурой получают преимущество при обработке. Результаты эксперимента не подтверждают теорию воплощенного познания, но нуждаются в воспроизведении. Обсуждаются рекомендации и дальнейшие направления исследования.

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Ключевые слова: воплощенное познание, глагол, кроссмодальный прайминг, лексическое решение, переходность глаголов, гипотеза «фасилитации сложностью»

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Литература

Ефремова Т.Ф. Новый словарь русского языка. Толково-словообразовательный. Т. 2. М.: Русский язык, 2000.

Ляшевская О.Н., Шаров С.А. Частотный словарь современного русского языка (на материалах Национального корпуса русского языка). М.: Азбуковник, 2009.

Alexeeva S., Slioussar N., Chernova D. StimulStat: A lexical database for Russian // Behavior Research Methods. 2018. Vol. 50. No. 6. P. 2305–2315. https://doi.org/10.3758/s13428-017-0994-3

Anwyl-Irvine A.L., Massonnié J., Flitton A., Kirkham N., Evershed J.K. Gorilla in our midst: An online behavioral experiment builder // Behavior Research Methods. 2020. Vol. 52. No. 1. P. 388–407. https://doi.org/10.3758/s13428-019-01237-x

Balota D.A., Yap M.J., Hutchison K.A., Cortese M.J., Kessler B., Loftis B., Neely J.H., Nelson D.L., Simpson G.B., Treiman R. The English lexicon project // Behavior Research Methods. 2007. Vol. 39. No. 3. P. 445–459. https://doi.org/10.3758/bf03193014

Barbieri E., Aggujaro S., Molteni F., Luzzatti C. Does argument structure complexity affect reading? A case study of an Italian agrammatic patient with deep dyslexia // Applied Psycholinguistics. 2015. Vol. 36. No. 3. P. 533–558. https://doi.org/10.1017/s0142716413000337

Barsalou L.W. Perceptual symbol systems // Behavioral and Brain Sciences. 1999. Vol. 22. No. 4. P. 577–660. https://doi.org/10.1017/s0140525x99002149

Bates D., Mächler M., Bolker B., Walker S. Fitting linear mixed-effects models using lme4 // Journal of Statistical Software. 2015. Vol. 67. No. 1. P. 1–48. https://doi.org/10.18637/jss.v067.i01

Buccino G., Colagè I., Silipo F., D'Ambrosio P. The concreteness of abstract language: An ancient issue and a new perspective // Brain Structure and Function. 2019. Vol. 224. P. 1385–1401. https://doi.org/10.1007/s00429-019-01851-7

Caramazza A., Anzellotti S., Strnad L., Lingnau A. Embodied cognition and mirror neurons: A critical assessment // Annual Review of Neuroscience. 2014. Vol. 37. No. 1. P. 1–15. https://doi.org/10.1146/annurev-neuro-071013-013950

Carreiras M., Mechelli A., Estévez A., Price C.J. Brain activation for lexical decision and reading aloud: Two sides of the same coin? // Journal of Cognitive Neuroscience. 2007. Vol. 19. No. 3. P. 433–444. https://doi.org/10.1162/jocn.2007.19.3.433

Engel L.R., Frum C., Puce A., Walker N.A., Lewis J.W. Different categories of living and non-living sound-sources activate distinct cortical networks // NeuroImage. 2009. Vol. 47. No. 4. P. 1778–1791. https://doi.org/10.1016/j.neuroimage.2009.05.041

García A.M., Ibáñez A. A touch with words: Dynamic synergies between manual actions and language // Neuroscience & Biobehavioral Reviews. 2016. Vol. 68. P. 59–95. https://doi.org/10.1016/j.neubiorev.2016.04.022

Harrison X.A., Donaldson L., Correa-Cano M.E., Evans J., Fisher D.N., Goodwin C.E.D., Robinson B.S., Hodgson D.J., Inger R. A brief introduction to mixed effects modelling and multi-model inference in ecology // PeerJ. 2018. Vol. 6. P. e4794:1–32. https://doi.org/10.7717/peerj.4794

Hauk O., Johnsrude I., Pulvermüller F. Somatotopic representation of action words in human motor and premotor cortex // Neuron. 2004. Vol. 41. No. 2. P. 301–307. https://doi.org/10.1016/s0896-6273(03)00838-9

Keuleers E., Brysbaert M. Wuggy: A multilingual pseudoword generator // Behavior Research Methods. 2010. Vol. 42. No. 3. P. 627–633. https://doi.org/10.3758/brm.42.3.627

Kiefer M., Sim E.-J., Herrnberger B., Grothe J., Hoenig K. The sound of concepts: Four markers for a link between auditory and conceptual brain systems // Journal of Neuroscience. 2008. Vol. 28. No. 47. P. 12224–12230. https://doi.org/10.1523/jneurosci.3579-08.2008

Klepp A., van Dijk H., Niccolai V., Schnitzler A., Biermann-Ruben K. Action verb processing specifically modulates motor behaviour and sensorimotor neuronal oscillations // Scientific Reports. 2019. Vol. 9. No. 1. P. 15985:1–11. https://doi.org/10.1038/s41598-019-52426-9

Kousta S.-T., Vinson D.P., Vigliocco G. Emotion words, regardless of polarity, have a processing advantage over neutral words // Cognition. 2009. Vol. 112. No. 3. P. 473–481. https://doi.org/10.1016/j.cognition.2009.06.007

Lemaitre G., Pyles J.A., Halpern A.R., Navolio N., Lehet M., Heller L.M. Who's that knocking at my door? Neural bases of sound source identification // Cerebral Cortex. 2018. Vol. 28. No. 3. P. 805–818. https://doi.org/10.1093/cercor/bhw397

Lo S., Andrews S. To transform or not to transform: Using generalized linear mixed models to analyse reaction time data // Frontiers in Psychology. 2015. Vol. 6. P. 1171:1–16. https://doi.org/10.3389/fpsyg.2015.01171

Lynott D., Connell L., Brysbaert M., Brand J., Carney J. The Lancaster Sensorimotor Norms: Multidimensional measures of perceptual and action strength for 40,000 English words // Behavior Research Methods. 2019. Vol. 52. No. 3. P. 1271–1291. https://doi.org/10.3758/s13428-019-01316-z

Mahon B.Z., Caramazza A. A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content // Journal of Physiology-Paris. 2008. Vol. 102. No. 1–3. P. 59–70. https://doi.org/10.1016/j.jphysparis.2008.03.004

Malyutina S., den Ouden D.-B. Task-dependent neural and behavioral effects of verb argument structure features // Brain and Language. 2017. Vol. 168. P. 57–72. https://doi.org/10.1016/j.bandl.2017.01.006

Mirabella G., Iaconelli S., Spadacenta S., Federico P., Gallese V. Processing of hand-related verbs specifically affects the planning and execution of arm reaching movements // PLoS ONE. 2012. Vol. 7. No. 4. P. e35403:1–14. https://doi.org/10.1371/journal.pone.0035403

Murteira A., Sowman P.F., Nickels L. Taking action in hand: Effects of gesture observation on action verb naming // Language, Cognition and Neuroscience. 2019. Vol. 34. No. 3. P. 351–364. https://doi.org/10.1080/23273798.2018.1552978

Paivio A., Yuille J.C., Madigan S.A. Concreteness, imagery, and meaningfulness values for 925 nouns // Journal of Experimental Psychology. 1968. Vol. 76. No. 1, Pt.2. P. 1–25. https://doi.org/10.1037/h0025327

Popp M., Trumpp N.M., Kiefer M. Feature-specific event-related potential effects to action- and sound-related verbs during visual word recognition // Frontiers in Human Neuroscience. 2016. Vol. 10. P. 637:1–16. https://doi.org/10.3389/fnhum.2016.00637

Popp M., Trumpp N.M., Kiefer M. Processing of action and sound verbs in context: An fMRI study // Translational Neuroscience. 2019. Vol. 10. No. 1. P. 200–222. https://doi.org/10.1515/tnsci-2019-0035

Popp M., Trumpp N.M., Sim E.-J., Kiefer M. Brain activation during conceptual processing of action and sound verbs // Advances in Cognitive Psychology. 2019. Vol. 15. No. 4. P. 236–255. https://doi.org/10.5709/acp-0272-4

Powers K.L., Brooks P.J., Aldrich N.J., Palladino M.A., Alfieri L. Effects of video-game play on information processing: A meta-analytic investigation // Psychonomic Bulletin & Review. 2013. Vol. 20. No. 6. P. 1055–1079. https://doi.org/10.3758/s13423-013-0418-z

Pulvermüller F. Brain mechanisms linking language and action // Nature Reviews Neuroscience. 2005. Vol. 6. No. 7. P. 576–582. https://doi.org/10.1038/nrn1706

Pulvermüller F., Hauk O., Nikulin V.V., Ilmoniemi R.J. Functional links between motor and language systems // European Journal of Neuroscience. 2005. Vol. 21. No. 3. P. 793–797. https://doi.org/10.1111/j.1460-9568.2005.03900.x

Rizzolatti G., Sinigaglia C. The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations // Nature Reviews Neuroscience. 2010. Vol. 11. No. 4. P. 264–274. https://doi.org/10.1038/nrn2805

Rofes A., Mahon B.Z. Naming: Nouns and verbs // Intraoperative mapping of cognitive networks / E. Mandonnet, G. Herbert (Eds.). Switzerland: Springer International Publishing, 2021. P. 171–194. https://doi.org/10.1007/978-3-030-75071-8_11

RStudio Team. RStudio: Integrated development environment for R. Boston, MA: 2020. URL: http://www.rstudio.com/.

Sato M., Mengarelli M., Riggio L., Gallese V., Buccino G. Task related modulation of the motor system during language processing // Brain and Language. 2008. Vol. 105. No. 2. P. 83–90. https://doi.org/10.1016/j.bandl.2007.10.001

So W.-C., Yi-Feng A.L., Yap D.-F., Kheng E., Yap J.-M.M. Iconic gestures prime words: Comparison of priming effects when gestures are presented alone and when they are accompanying speech // Frontiers in Psychology. 2013. Vol. 4. P. 779:1–9. https://doi.org/10.3389/fpsyg.2013.00779

Tettamanti M., Buccino G., Saccuman M.C., Gallese V., Danna M., Scifo P., Fazio F., Rizzolatti G., Cappa S.F., Perani D. Listening to action-related sentences activates fronto-parietal motor circuits // Journal of Cognitive Neuroscience. 2005. Vol. 17. No. 2. P. 273–281. https://doi.org/10.1162/0898929053124965

Thompson C.K. Unaccusative verb production in agrammatic aphasia: The argument structure complexity hypothesis // Journal of Neurolinguistics. 2003. Vol. 16. No. 2–3. P. 151–167. https://doi.org/10.1016/s0911-6044(02)00014-3

Thompson C.K., Lange K.L., Schneider S.L., Shapiro L.P. Agrammatic and non-brain-damaged subjects' verb and verb argument structure production // Aphasiology. 1997. Vol. 11. No. 4–5. P. 473–490. https://doi.org/10.1080/02687039708248485

Veale J.F. Edinburgh Handedness Inventory — Short Form: A revised version based on confirmatory factor analysis // Laterality: Asymmetries of Body, Brain and Cognition. 2014. Vol. 19. No. 2. P. 164–177. https://doi.org/10.1080/1357650x.2013.783045

Yap D.-F., So W.-C., Melvin Yap J.-M., Tan Y.-Q., Teoh R.-L.S. Iconic gestures prime words // Cognitive Science. 2011. Vol. 35. No. 1. P. 171–183. https://doi.org/10.1111/j.1551-6709.2010.01141.x