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Second language embodiment of action verbs: the impact of bilingual experience as a multidimensional spectrum

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Abstract

Embodiment theories postulate that language processing inherently engages the sensorimotor system. This study explores the embodiment of action verbs in the second language (L2) and the effects of various L2 experiences (L2 age of acquisition, exposure, dominance, and proficiency) on L2 embodiment. Sixty-one Chinese–English bilinguals participated in two experiments judging semantic relatedness: Experiment 1 involved verb–picture pairs, while Experiment 2 focused on verb–verb pairs. Both experiments were conducted in the participants' first language (Chinese) and second language (English), with the stimuli depicting actions performed by specific effectors (e.g., mouth, hand, and foot). Results showed that participants took longer to reject mismatched verb–picture pairs and semantic-unrelated verb–verb pairs when the actions shared the same effector (e.g., walk–run) than those involving different effectors (e.g., eat–touch). Moreover, L2 age of acquisition, exposure, and dominance correlated with the L2 embodiment effect, with L2 age of acquisition and exposure modulating this effect. This study enhances our understanding of L2 embodied semantics and illuminates the impact of multidimensional L2 experiences on embodiment.

Highlights

- Provides further empirical evidence that second language (L2) processing partially employs an embodied mechanism.
- Systematically shows that L2 age of acquisition (AoA), L2 exposure and L2 dominance correlate with the L2 embodiment effect.
- Reveals that L2 AoA and L2 exposure modulate the L2 embodiment, with L2 exposure playing a more significant role.
- Contributes novel insights into L2 embodiment and suggests a future research direction that integrates both embodied and disembodied perspectives.

1. Introduction

The traditional symbolic theory proposed that concepts are represented as abstract and amodal symbols (Binder, 2016; Fodor, 1975; Pylyshyn, 1984). However, the emergence of the embodied perspective challenged this view by postulating that conceptual knowledge is grounded in sensorimotor mechanisms (Barsalou, 2008). Specifically, language processing activates linguistic and nonverbal multimodal representations (e.g., sensations, emotions, and actions) associated with the depicted event. This embodiment effect stems from the collaboration between a linguistic system conveying meaning through words and a simulation system employing sensorimotor memories to recreate real-life experiences (Anderson et al., 2019; Bi, 2021).

Numerous studies have provided supporting evidence for this assertion: first language (L1) semantic comprehension spontaneously evokes perceptual (e.g., Sato et al., 2013; Winter & Bergen, 2012; Yaxley & Zwaan, 2007) and motor (e.g., Fischer & Zwaan, 2008; Glenberg & Kaschak, 2002; Pulvermüller & Fadiga, 2010; Zhang et al., 2020) information that aligns with the linguistic descriptions of perceptions and actions. For example, encountering a sentence such as "She gave him a warm smile" triggers neural pathways associated with the sensation of physical warmth (e.g., Sato et al., 2013). Similarly, reading a sentence like "He grasped the cup tightly" can evoke neural responses in the motor cortex linked to hand movements despite no physical action (e.g., Pulvermüller & Fadiga, 2010).

While most research in this field has focused on the L1 embodiment, there has been limited exploration of the second language (L2) embodiment. As is well-known, L1 is typically acquired through daily interactive experiences involving diverse scenarios and integrated multimodal exposures, potentially leading to a robust L1 embodiment (Jeong et al., 2021; Li & Jeong, 2020). In contrast, formal L2 acquisition is usually characterized by a lack of exposure to and interactions

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with multimodal stimuli (Li & Jeong, 2020; Norman & Peleg, 2022). Thus, L2 semantic representations may involve less sensorimotor information and have weaker connections to real-life experiences (Ahlberg et al., 2017; Tian et al., 2020). The distinct learning experiences between L1 and L2 contribute to variations in their semantic representations.

Although non-proficient bilinguals activate their L1 during L2 processing (Li et al., 2018), it remains uncertain whether L2 processing engages the perceptual and motor simulation and whether the simulation arises from the automatic L1 activation during L2 processing or reflects the embodied characteristics of L2. Furthermore, individual variations in bilingual learning experience, conceptualized as a multidimensional spectrum (DeLuca et al., 2019; Gullifer et al., 2021), may modulate the extent to which L2 processing recruits the embodied mechanism. Therefore, this study aims to investigate L2 embodiment in the semantic processing of action verbs among Chinese–English bilinguals and assess how diverse multidimensional bilingual experiences influence this effect.

1.1. L1 and L2 embodiment in bilinguals

Over the past decades, extensive research has demonstrated that L1 semantic processing is inherently linked with the sensorimotor system (e.g., Bergen et al., 2010; Glenberg & Kaschak, 2002; Marino et al., 2014). These studies used behavioral experimental paradigms, such as verb–picture matching tasks, go/no-go tasks or semantic judgment tasks, uncovering the cognitive mechanisms underlying language processing. Building on the established groundwork, we review the existing literature, concentrating specifically on processing action-related language.

In the verb–picture matching task (e.g., Bergen et al., 2010), a widely used paradigm in this field, native English and Cantonese speakers viewed action verbs (e.g., jump) paired with corresponding pictures (e.g., a drawing depicting jumping). The verbs either appropriately described the depicted action (e.g., jump) or did not (e.g., walk). Participants judged whether each picture semantically matched the preceding verb. Unknown to them, in the verb–picture mismatched condition ("No" response), there were two types of picture stimuli, one (e.g., walk.jpg) implicating the same effector (i.e., feet) as the verb (jump) and the other (e.g., eat.jpg) implying a different effector (i.e., mouth). In the mismatched condition where a "No" response occurred (same-effector vs. different-effector), embodiment effects emerged if response times for the same-effector pairs (e.g., jump vs. walk.jpg) were slower than those for the different-effector pairs (e.g., jump vs. eat.jpg). This embodiment effect, calculated as the difference in response time between the same and different effectors, may arise from interference caused by mentally simulating the original action (Bergen et al., 2010). In their study, Bergen et al. (2010) found that participants took significantly longer to determine mismatches between pictures and verbs when they shared an effector compared to when they did not.

Consistent with the behavioral findings, researchers have utilized sophisticated neuroimaging technologies and other neurological tools to delve deeper into the neural substrates of sensorimotor engagement in L1 semantic processing (Hauk et al., 2004; Johari et al., 2022; Klepp et al., 2014; Tettamanti et al., 2005). Klepp et al. (2014) used magnetoencephalography to examine the involvement of sensorimotor areas in processing action-related verbs. They studied native German speakers who silently read individual action verbs describing hand, foot or non-body actions on a screen and then made lexical decisions. The results showed activation of specific brain areas (e.g., primary motor cortex) responsible for hand and foot motor control during silent reading of the verbs related to these corresponding effectors. More recently, Johari et al. (2022) explored the neural underpinnings of action word processing by examining the effects of high-definition transcranial direct current stimulation on primary and higher-order motor areas while English speakers performed lexical decision and semantic similarity judgment tasks. The study revealed that the targeted motor areas facilitated action-related language processing, suggesting specialized roles for these areas in action semantics.

While considerable evidence supports semantic embodiment in L1 processing, limited attention has focused on L2 embodiment and its modulators (Kühne & Gianelli, 2019; Monaco et al., 2019; Zhang et al., 2020). Some researchers contend that L2 processing demonstrates semantic embodiment comparable to L1, as both languages engage similar cognitive and neural mechanisms (Ahn & Jiang, 2018; Buccino et al., 2017; De Grauwe et al., 2014; Dudschig et al., 2014). These studies have observed L2 embodiment effects in multiple tasks like Stroop tasks and go/no-go paradigms or through neuroimaging technologies such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) measurements, though some studies note that the L2 embodiment effects may not be as robust as those in L1 (e.g., Ahlberg et al., 2017; Tian et al., 2020; Vukovic & Shtyrov, 2014; Zhang et al., 2020). For example, Vukovic and Shtyrov (2014) observed a reduced embodiment in L2 semantic processing by investigating German–English bilinguals' motor-cortex recruitment in processing action verbs. They used high-density EEG to track cortical motor system activity changes as participants read action words in L1 and L2. The results reflected rapid motor-cortex involvement during action-semantic processing in both languages, but there was a decreased motor activation in L2 compared to L1. This phenomenon implied the presence of more integrated action-perception substrates formed in L1 processing.

Conversely, some investigations suggest that L2 embodiment may resemble L1, indicating a common underlying mechanism. For instance, Buccino et al. (2017) used a go/no-go paradigm to test whether fluent L2 speakers would exhibit similar motor system modulation when processing graspable nouns in L2 as they would in L1. The study presented fluent Italian–English bilinguals with English nouns and images of graspable and non-graspable objects as stimuli, as well as pseudowords and scrambled images as controls. Participants were tasked with pressing a key when the stimulus represented a real object and refraining from responding to the scrambled or pseudo stimuli. The results displayed that graspable items (both images and nouns) elicited slower responses than non-graspable ones, consistent with the expected pattern in L1, suggesting that fluent L2 speakers engage the motor system similarly, irrespective of language. While the study did not present a direct within-participant comparison of L1 and L2 processing, its results align with a previous experiment by Marino et al. (2014) that utilized the same paradigm with Italian native speakers processing similar stimuli in L1.

However, other research findings challenge the notion of L2 embodiment, positing that the formal acquisition of L2 is usually devoid of the rich sensorimotor experiences inherent in L1, thereby lacking robust perceptual and motor simulations during L2 comprehension (Chen et al., 2020; Norman & Peleg, 2022). Their empirical results also revealed an absence of L2 embodiment effects. For example, Chen et al. (2020) investigated Cantonese–Mandarin–English trilinguals in a delayed sentence–picture verification (SPV) task. Participants identified whether objects depicted in presented pictures were mentioned in preceding sentences. These sentences, such as "The boy saw a car driving past," either matched (e.g., "a car is driving on the road") or mismatched (e.g., "a car is parked in the garage") the pictured objects in perceptual features (e.g., shapes, sizes, and positions). If language comprehension is embodied, the match condition should have facilitated verification, leading to faster responses than the mismatch condition. However, results showed that this facilitation effect was only evident in L1, with no effect observed in L2 or L3, even among highly proficient L2 speakers.

Using a similar paradigm, Norman and Peleg (2022) documented that proficient Hebrew–English bilinguals exhibited quicker response times when the shape of the depicted object matched the shape implied by the sentence. Nonetheless, this effect manifested exclusively in L1, specifically when the L1 block preceded the L2 block. The two studies suggest that the diminished embodiment in L2 is likely due to less integrated linguistic and perceptual representations in L2 comprehension. Similarly, Morey et al. (2021) conducted a multi-lab, preregistered replication study to test the action–sentence compatibility effect (ACE) proposed by Glenberg & Kashak (2002). ACE denotes the phenomenon where responses are faster when the movement direction aligns with the action described in a sentence. Multiple labs participated in the experiment, where both native and non-native English speakers made sensibility judgments (by executing movements toward or away from the body) based on sentences describing actions either toward (e.g., "Tom handed the pen to you") or away from (e.g., "You handed the pen to Tom") their bodies. However, none of the labs observed a reliable ACE in L1 or L2.

The above inconsistent findings lead to the ongoing debate surrounding whether semantic processing in L2 and even L1, involves the recruitment of sensorimotor resources. Furthermore, empirical evidence (Anderson et al., 2019; Momenian et al., 2021) and theoretical assumptions (e.g., the dual-coding knowledge neural framework from Bi, 2021; Wang et al., 2020) have emerged, postulating an integrated view that language comprehension encompasses both symbolic and embodied mechanisms, highlighting the need for more robust empirical studies to delve deeper into the L2 embodiment effect.

In addition, we should note that the embodiment effects elicited from the SPV and the ACE are typically construed as facilitation effects, which occur when congruent sensorimotor activation enhances cognitive performance, leading to faster processing speeds due to consistency between sensorimotor activation and the cognitive task. Conversely, inhibitory effects, also termed interference effects (e.g., observed in the verb–picture matching task), arise when incongruent sensorimotor activation hinders cognitive performance, in which a discrepancy between sensorimotor activation and the cognitive task results in slower processing speeds.

Although these two effects, reflecting how sensorimotor experiences influence cognitive processes, have been extensively investigated, there is substantial debate regarding whether embodiment effects are facilitatory or inhibitory and what determines the direction of these effects (Momenian et al., 2024; Montero-Melis et al., 2022; Shebani & Pulvermüller, 2013; Zeelenberg & Pecher, 2016). Relevant research suggests that task complexity (e.g., Shebani & Pulvermüller, 2018), specific contexts (e.g., Tsaregorodtseva & Kaup, 2024; von Sobbe et al., 2021) and task execution (e.g., Winter et al., 2022) potentially influence the direction of these effects. Moreover, studies have demonstrated that facilitatory and inhibitory effects coexist within the same experimental paradigm (Buccino et al., 2016; Zwaan & Pecher, 2012). Thus, Ostarek and Huettig (2019) highlighted that one of the critical challenges for embodiment research is to clarify these effects' directions and identify which paradigms (facilitation or interference) could indicate a causal role of the sensorimotor system in embodiment effects. Some studies suggested that the facilitation effect alone may not fully demonstrate the functional role of sensorimotor systems in language processing, although it does indicate their involvement (Bergen, 2008; Ostarek & Huettig, 2019). On the contrary, despite mixed evidence in the literature (Montero-Melis et al., 2022; Zeelenberg & Pecher, 2016), the interference effect comparatively holds promise in illuminating sensorimotor simulation (Ostarek & Bottini, 2021). Considering these factors, the present study proposes to adopt the interference paradigm to explore the involvement of the sensorimotor system in L2 semantic processing and its potential modulators.

1.2. Bilingual experience and L2 embodiment

Recent evidence underscores that bilingual experience is a multidimensional spectrum (Gullifer et al., 2021; Luk & Bialystok, 2013; Li & Dong, 2020), encompassing multiple experience-based factors such as L2 age of acquisition (AoA), L2 proficiency, L2 exposure, and L2 dominance (e.g., DeLuca et al., 2019; Li et al., 2019). Several studies have proposed that L2 proficiency modulates L2 embodiment effects (e.g., Bergen et al., 2010; Birba et al., 2020; Gu et al., 2021; Tang et al., 2023; Vukovic, 2013). For example, Birba et al. (2020) investigated how embodied semantic systems interacted with varying levels of L2 proficiency for Spanish–English bilinguals. Participants read action and neutral texts naturally in both languages, while EEG was used to track their neural activities. Results showed higher L2 proficiency correlated with enhanced EEG functional motor-related connectivity during L2 action text reading. Similarly, Tang et al. (2023) instructed Chinese-English bilinguals to perform an emotional valence categorization task in both languages, where participants assessed whether the given words were positive, negative or neutral. Findings revealed faster responses in L2 among participants with higher English proficiency.

Nevertheless, studies by Chen et al. (2020), Kogan et al. (2020a), Monaco et al. (2023), and Zhang et al. (2020) suggest that L2 proficiency exerts minimal influence on the embodied representations in L2 processing. Specifically, in an fMRI study, Zhang et al. (2020) investigate embodied semantics in L2 processing. Participants judged the semantic relatedness of English words. Researchers found that Chinese–English bilinguals, regardless of proficiency level, primarily engaged the semantic system during L2 processing, unlike native speakers whose sensorimotor systems were connected with the semantic system. The discrepancy in findings regarding the L2 proficiency modulation effects on L2 embodiment may stem from differences in the tasks' ecological validity and the measures of proficiency assessed. As a whole, existing literature presents varied perspectives on the relationship between L2 proficiency and L2 embodiment, underscoring the intricate nature of this relationship.

Within the limited body of research on L2 embodiment, prior studies have primarily focused on examining the association between L2 proficiency and L2 embodiment. Concerning the influence of L2 AoA, Monaco et al. (2019) noted in a review that existing findings showed early bilinguals' L2 semantic processing engages sensorimotor areas to a similar extent as their L1, implying a potential impact of L2 AoA on L2 embodiment. This proposition gained support from specific investigations. As illustrated earlier, Norman and Peleg (2022) observed attenuated perceptual simulations in late Hebrew–English bilinguals during an SPV task in their

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L2. These observations were in line with prior literature. For instance, Caldwell-Harris et al. (2011) examined late Chinese–English bilinguals' perception of emotional content, asking them to judge words' emotionality in L1 and L2 through the bilingualism and emotions questionnaire (Dewaele, 2010). The authors discovered that late bilinguals perceived their L1-Chinese as more emotional, while early bilinguals rated both languages equally emotional. Pavlenko (2012) further indicated in a review that later-acquired languages rely more on semantic than emotional processing mechanisms. However, Kogan et al. (2020b) noted from their review that some studies showed adult learners could also experience sensorimotor resonance shortly after exposure to a new language, suggesting that L2 AoA may not invariably influence L2 embodiment effects. Therefore, further exploration is warranted to elucidate the role of L2 AoA in L2 embodiment.

In short, a few attempts have explored the role of L2 proficiency or L2 AoA in L2 embodiment. These studies typically regarded bilingualism as a categorical label, focusing on a single dimension, such as L2 proficiency or L2 AoA. However, bilingual individuals vary across multiple dimensions, including L2 exposure and L2 dominance related to language use (de Bruin, 2019; Li et al., 2019). These aspects have received limited attention in bilingual studies on embodiment to date. The current study seeks to address these questions by characterizing the bilingual experience along multiple dimensions (including L2 AoA, L2 proficiency, L2 exposure, and L2 dominance) on a continuum, aiming to elucidate how these dimensions of bilingual experience uniquely contribute to L2 embodiment.

2. The present study

The present study aims to investigate L2 embodiment and explore how bilingual experience may modulate this phenomenon. We conducted two experiments focusing on action verbs semantically associated with specific body parts known as effectors (e.g., mouth, hand, and foot). Experiment 1 employed the verb–picture matching paradigm to examine the automatic activation of effector information embedded in action verbs during L1 and L2 semantic comprehension (Bergen, 2008). Participants made match-or-not judgments of verb–picture pairs presented successively. A "Yes" response indicated matched actions, whereas a "No" response indicated mismatched actions, where verb–picture pairs denoted two distinct actions, with half of the pairs sharing effectors (same effector) and the other half not (different effector). Participants were unaware of these two sub-conditions (same effector vs. different effector) under the mismatched condition.

To eliminate potential visual confounds of pictures in Experiment 1, we employed a semantic judgment task based on verb–verb pairs in Experiment 2. Both experiments examined the modulation effects of L2 AoA, L2 proficiency, L2 exposure, and L2 dominance on the L2 embodiment effect. Participants performed equivalent tasks in their L1 and L2, allowing us to compare embodiment effects across languages and explore the possible influence of bilingual experience on the embodiment effect.

Participants were native Chinese speakers with English as their L2. We hypothesize that if L2 action words are grounded in body and motor information, embodiment effectors may modulate the processing of mismatched pairs in Experiment 1 (verb–picture) and semantically unrelated pairs in Experiment 2 (verb–verb). Specifically, we expect increased response times and error rates when participants reject unrelated semantic pairs sharing the same effectors compared to pairs with different effectors. Furthermore, considering the varying findings in the literature regarding the impact of bilingual experience on L2 embodiment, we anticipate that, along the spectrum of bilingualism, differences in learning experiences, such as the timing of L2 acquisition, L2 proficiency levels, and the extent of L2 exposure, contribute to variations in L2 embodiment. Specifically, individuals with rich learning experiences, characterized by early L2 acquisition, higher L2 proficiency, and substantial L2 exposure, are likely to have semantic systems more closely integrated with the sensorimotor system, thereby relying more on embodied mechanisms for language processing and exhibiting L1-like L2 embodiment. Conversely, those with limited L2 learning experiences, marked by late L2 acquisition, lower L2 proficiency, and minimal L2 exposure, may have semantic representations less connected to sensorimotor systems. Consequently, they may depend more on symbolic processing mechanisms and are less likely to display or even lack L2 embodiment effects. Therefore, variations in bilingual experience could modulate the observed differences in response patterns between same- and different-effector pairs, generating varying degrees of L2 embodiment.

3. Experiment 1

3.1. Method

3.1.1. Participants

Sixty-one healthy Chinese–English bilinguals (52 females; mean age: 21 ± 1.93 years) from Guangdong University of Foreign Studies participated in Experiment 1. They learned L2 (English) at an average age of 8 (*SD* = 2.01) in traditional classroom settings without travel experience (for more than 3 months) to a country or an area where English was the native language. The current study was approved by the Ethics Committee of the Bilingual Cognition and Development Lab at Guangdong University of Foreign Studies. Participants signed consent forms and received compensation for their participation.

3.1.2. Bilingual experience measures

All participants completed a brief version of the Language History Questionnaire (LHQ 3.0, Li et al., 2019), a widely used tool for assessing the language background of bilingual and multilingual individuals. The questionnaire comprises several modules, totaling 16 questions, covering demographics (e.g., age, gender, and education), linguistic background in both L1 and L2, language usage habits across various contexts, and self-assessed linguistic abilities (see sample questionnaire in Table S1 in the Supplementary Material). Among the four language experience dimensions, AoA was directly derived from the participants' self-reports. As for language proficiency, exposure and dominance, we quantitatively assessed them through aggregated scores, representing overall proficiency, exposure, and dominance levels in each learned language. These scores were computed from self-reported data, and we outlined their calculation methods as follows:

1) *AoA* represents the age at which an individual starts acquiring, learning or using a specific language. Participants reported the onset ages for Listening, Speaking, Reading, and Writing (hereafter *LSRW*). We determined AoA for each language by identifying the earliest reported age when participants began using it.

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2) *Language proficiency* pertains to an individual's competence in effectively understanding and producing a specific language. Participants evaluated their proficiency in *LSRW* for each language on a 7-point scale (1-very poor to 7-excellent). Each *LSRW* aspect carried equal weight (25%, the same applied to other dimensions below), contributing to the overall proficiency score based on the weighted sum of a participant's self-rated proficiency across different language aspects. Besides, participants completed the Oxford Quick Placement Test (QPT, Syndicate, 2001) for an objective English proficiency assessment ($M = 47.27$, $SD = 4.47$). Given the positive correlation between the L2 proficiency score obtained from the LHQ 3.0 and the QPT score ($r = .68$, $p = .003$), along with empirical evidence demonstrating that LHQ proficiency scores align well with objective language tests and predict linguistic competence reliably (e.g., Zhang et al. 2020), we chose the L2 proficiency score from LHQ 3.0 to maintain consistency in measurement across other bilingualism dimensions.
3) *Language exposure* denotes the time individuals dedicate to learning and using a language. Participants indicated their AoA (in *LSRW*) and the years they spent using each language, and then an aggregated exposure score for each language was computed based on age, AoA, and years of language use.
4) *Language dominance* relates to language usage patterns, highlighting the relative proficiency and usage of each language compared to the native language (Treffers-Daller, 2019; Treffers-Daller & Silva-Corvalán, 2015). Participants reported daily hours spent in various communicative contexts (e.g., conversation, social media, Internet, academic, and recreation) for each language in *LSRW*. We derived overall dominance aggregated scores from the participants' self-assessed proficiency and time allocation across these contexts.

The aggregated scores for proficiency, exposure and dominance were standardized within a range of 0–1 following LHQ's calculation methods, with 1 indicating the most native-like level. This quantification enabled us to assess participants' bilingual experiences across a spectrum from native-like to less native-like, summarized in Table 1. Please refer to Li et al. (2019) for more detailed methods for computing these scores.

Table 1. Language background of participants in Experiment 1

Measurements	Range	Mean	*SD*
L1 AoA[a]	0–4	1.05	1.46
L1 proficiency (0–1)[b]	0.64–1	0.84	0.10
L1 exposure (0–1)	0.68–0.96	0.87	0.08
L1 dominance (0–1)	–	1	0
L2 AoA	3–12	8.11	1.99
L2 proficiency (0–1)	0.29–0.86	0.62	0.11
L2 exposure (0–1)	0.37–0.79	0.61	0.09
L2 dominance (0–1)	0.36–0.89	0.71	0.12

[a]AoA = age of acquisition;
[b]The scores from LHQ have been normalized into a range between 0 and 1.

3.1.3. Design and stimuli

Experiment 1 employed a verb–picture matching paradigm that manipulated two categorical variables: language (L1, L2) and effector type (matched same-effector, mismatched same-effector, mismatched different-effector)[1]. As noted earlier, embodiment effects in this experimental paradigm are indicated by slower responses to same-effector pairs compared to different-effector pairs in the mismatched condition, which were the primary focus of our analysis. Therefore, consistent with the prior research (Bergen et al., 2010), we directly compared the critical differences between same-effector and different-effector sub-conditions using a 2 (Language: L1, L2) × 2 (Effector type: same-effector, different-effector) within-participant design. Moreover, we included L2 AoA, L2 proficiency, L2 exposure, and L2 dominance as continuous variables to assess bilingual experience.

Fifty-two black-and-white stick figures served as picture stimuli: 30 were adapted from Bergen et al. (2010), and the remaining 22 were created by the experimenter of this study. These pictures depicted motor actions primarily performed by specific effectors, including mouth/face (17), hand/arm (22), and foot/leg (13), illustrated in Table 2. Accordingly, we selected 52 English and 52 Chinese verbs to match the picture stimuli[2], which made for matched verb–picture pairs. We used the same set of verbs from the matched pairs to create the mismatched verb–picture pairs, in which we randomly assigned each picture a verb representing a different action with the same effector (e.g., lick–scream.jpg) and a verb depicting an action with different effectors (e.g., kick–scream.jpg). English action verbs consisted of one-syllable words with 3–7 letters. Chinese action verbs included one-character words (e.g., "跑[run]," "吃[eat]") and two-character words corresponding to single English verbs (e.g., "私语[whisper]," "溜冰[ski]").

We recruited 20 participants (from the same university as the participants but did not participate in the experiments) to rate the familiarity, imageability, visual complexity, and degree of effector involvement of the picture and verb stimuli on a 7-point scale. Chinese and English verb frequencies were derived from the frequency dictionaries by Cai and Brysbaert (2010) and Brysbaert and New (2009). All the verbs were high-frequent words (Chinese: $M = 2739.56$, $SD = 532.22$; English: $M = 156.58$, $SD = 320.06$). These frequencies, strokes of Chinese verbs and word length of English verbs matched across different conditions (see Table S2 for details in the Supplementary Material).

Overall, each participant completed the verb–picture matching task in L1 and L2. Each language block contained 52 verb–picture matched pairs and 52 verb–picture mismatched pairs. Half of the mismatched pairs shared the same effector, and half did not. Our focus was comparing the mismatched pairs with the same effector and those with different effectors during L1 and L2 processing.

3.1.4. Procedure

Chinese and English blocks were counterbalanced across participants. The matched and mismatched verb–picture pairs were presented in a pseudorandomized order in each block. Each trial started with a 500-ms fixation at the center of the screen, followed by an action verb lasting 1500 ms and then a 500-ms blank interval. The target picture then appeared for a maximum of 2000 ms or stopped upon responses (Figure S1). Participants were requested to

[1]The matched different-effector sub-condition was unavailable due to the rarity of verb–picture pairs that meet both criteria simultaneously.

[2]Twenty participants provided each picture with three best verbs to describe the action depicted by the picture, in Chinese and English, respectively. The most frequently suggested verb was selected as the matching verb.

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Table 2. Sample stimuli of Experiment 1

Languages	Effector type		Verbs	Pictures
L1: Chinese	Matched	Same-effector (52)	踢(kick)	
	Mismatched	Same-effector (26)	走(walk)	
		Different-effector (26)	切(cut)	
L2: English	Matched	Same-effector (52)	kick	
	Mismatched	Same-effector (26)	walk	
		Different-effector (26)	cut	

Note: L2 stimuli are equivalent to L1 in terms of meaning. The numbers in parentheses following each effector type indicate the number of verb–picture pairs.

accurately and quickly indicate whether the picture matched the preceding verb by pressing the Yes/No buttons, counterbalanced across participants. E-prime 2.0 (Psychology Software Tools Inc., Pittsburgh, USA) was used for programming and data collection encompassing reaction times (RTs) and accuracy.

3.2. Data analysis and results

All participants had more than 70% accuracy rates, so no one was excluded from the data analysis. Incorrect responses (4.81%) and outliers ($M \pm 3$ *SD*s per participant under each condition) were removed from the RT data (0.98%). Table 3 summarizes the descriptive statistics of RT and accuracy rates. Given our focus, we only analyzed the mismatched pairs with same-effectors and different-effectors to examine the L2 embodiment effect.

Table 3. Mean (SD) reaction times and accuracy rates for matched and mismatched (same-/different-effector) conditions in Experiment 1 and semantic-related and semantic-unrelated (same-/different-effector) conditions in Experiment 2

	RT (ms)		Accuracy rates (%)	
Effector type	L1	L2	L1	L2
Experiment 1				
Matched	688.21 (222.84)	746.34 (276.55)	96.72 (3.15)	93.10 (5.49)
Mismatched same-effector	739.68 (229.03)	790.05 (269.14)	95.84 (3.60)	92.50 (8.54)
Mismatched different-effector	693.50 (210.16)	745.58 (256.49)	98.36 (2.76)	95.77 (5.95)
Experiment 2				
Semantic-related	672.44 (222.80)	821.12 (288.55)	95.33 (3.99)	75.8 (11.62)
Semantic-unrelated same-effector	708.26 (222.37)	849.46 (260.74)	95.61 (3.94)	90.90 (7.42)
Semantic-unrelated different-effector	654.70 (184.34)	800.72 (240.28)	97.65 (3.68)	96.24 (5.09)

Note: RT = reaction time.

3.2.1. L2 embodiment effect

We applied linear mixed-effects models (LME) to log-transformed RTs in the statistical software R (version 4.3.1, R Core Team, 2023) using the *lme4* (version 1.1-27, Bates et al., 2015) and the *lmerTest* packages (version 3.1-3, Kuznetsova et al., 2017). To examine the embodiment effect in L1 and L2, we constructed a basic model with language (L1, L2), effector type (same-effector, different-effector) and their interactions as fixed effects. Contrast coding was performed for language (L1 = −0.5, L2 = 0.5) and effector type (different-effector = −0.5, same-effector = 0.5). We started with the maximal random effects structure, which covered random intercepts for participants and items and random slopes for all predictors (Barr et al., 2013; Matuschek et al., 2017). When the model failed to converge, we removed the terms in the random effects structure that could not significantly improve the model's goodness of fit. The final model included by-participant and by-item random intercepts, and by-participant random slopes for language. Significance (*p*-value) was evaluated using the Satterthwaite approximation (Kuznetsova et al., 2017).

Figure 1A presents the RTs from the verb–picture matching task. The main effect of the effector type was significant ($\beta = 0.06$, $SE = 0.02$, $t = 3.53$, $p < .001$). Figure 1A and Table 3 show that participants took longer to make match-or-not judgments in the same-effector sub-condition ($M = 765 \pm 249$ ms) than in the different-effector sub-condition ($M = 720 \pm 233$ ms), indicating an embodiment effect ($RT_{\text{same-effector}} > RT_{\text{different-effector}}$). The main effect of language was significant as well ($\beta = 0.07$, $SE = 0.02$, $t = 3.33$, $p < .01$), with faster responses in L1 ($M = 717 \pm 220$ ms) than in L2 ($M = 768 \pm 263$ ms), showing semantic processing differences between the two languages. The interaction effect between language and effector type was not significant ($\beta = -0.001$, $SE = 0.01$, $t = -0.12$, $p = .91$). We further examined the main effect of effector type for L1 and L2, respectively, revealing that semantic comprehension of action-related verbs exhibited embodiment effects in both languages: L1 ($\beta = -0.06$, $SE = 0.02$, $t = -3.45$, $p < .001$) and L2 ($\beta = -0.06$, $SE = 0.02$, $t = -3.20$, $p < .01$), paving the way for exploring the impact of bilingualism on L2 embodiment in subsequent analyses.

3.2.2. Correlations between bilingual experience and L2 embodiment

We analyzed the relationship between bilingual experience and L2 embodiment by correlating the four dimensions of bilingual experience with the L2 embodiment effect. Bilingual experiences were

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quantified using the aggregated scores (see Table 1) of L2 AoA, L2 proficiency, L2 exposure, and L2 dominance. The L2 embodiment effect was calculated as the RT difference between the same and different effector sub-conditions (Difference score = $RT_{same\text{-}effector} - RT_{different\text{-}effector}$). Figure 1B illustrates the significant correlations between L2 AoA, L2 exposure, and L2 dominance with the L2 embodiment effect, which was unrelated to L2 proficiency.

3.2.3. Modulation effect of bilingual experience

To examine the distinct modulation effects of L2 AoA, L2 exposure, L2 proficiency, and L2 dominance on L2 embodiment, we added each dimension of bilingual experiences one at a time to the prior basic mixed-effects model and constructed four models, respectively. In each model, fixed effects included language, effector type, one dimension of bilingual experience and their interactions (except models 3 and 4)[3]. When the maximal random effects structure met convergence issues, we iteratively simplified each model by removing random effect terms that accounted for the least variance until the model converged. Finally, each model's best-fitting random effects structure included by-participant and by-item random intercepts alongside by-participant random slopes for Language. Since the effector type denoted the L2 embodiment effect, the interactions between the effector type and the four dimensions of bilingual experience estimated the modulation effect of bilingual experience on L2 embodiment. Table 4 displays the results of the four models.

In what follows, considering our theoretical focus on how bilingual experience modulates the L2 embodiment effect, we primarily concentrated on the interaction effect between the effector type (same-effector vs. different-effector) and the four dimensions of bilingual experience. We employed the releveling/nested effects to analyze these interactions, which entails rearranging levels within independent variables (e.g., language) to create subsets based on specific combinations of variables (e.g., Effector type × L2 AoA).

In model 1 (concerning L2 AoA), we found a significant two-way interaction between the effector type and L2 AoA. Critically, a three-way interaction involving effector type, language, and L2 AoA was also significant. Follow-up analysis of the three-way interaction showed that the Effector type × L2 AoA two-way interaction was significant ($\beta = -0.01$, $SE = 0.005$, $t = -3.16$, $p = .002$) in L2 processing (Figure 2) but not in L1 ($\beta = 0.001$, $SE = 0.004$, $t = 0.14$, $p = .89$). Specifically, the L2 embodiment effect was evident when L2 AoA was before 9.5 years old[4], while this effect diminished beyond this age threshold. Besides, the nonsignificant Effector type × Language interaction (when L2 AoA was before 9.5) implied that bilinguals engage the sensorimotor system similarly in L2 as in L1 when acquiring an L2 at a relatively young age.

In model 2 (concerning L2 exposure), the interaction between Effector type and L2 exposure was significant. Crucially, the three-way interaction of Effector type × Language × L2 AoA was also significant. Further analyses indicated a significant Effector type × L2 exposure interaction ($\beta = 0.34$, $SE = 0.10$, $t = 3.54$, $p < .001$) in L2 processing (Figure 2) but not in L1 ($\beta = 0.01$, $SE = 0.08$, $t = 0.12$, $p = .91$). Specifically, the L2 embodiment effect occurred when L2 exposure ranged from 0.55 to 0.79[5], but it was not evident at lower levels (0.37–0.55). In addition, the nonsignificant Effector type × Language interaction (when L2 exposure exceeded 0.55) suggested that L2 semantic processing entails the sensorimotor system to a similar extent as native language processing when bilinguals have relatively sufficient exposure to an L2. Furthermore, we conducted a principal component regression analysis to explore the individual contributions of the four dimensions to the L2 embodiment effect. The analysis revealed that L2 exposure had the greatest relative weight (see supplementary Text 1, Tables S3 and S4 and Figure S2 for details in the Supplementary Material), indicating a crucial role of L2 exposure in facilitating the employment of embodied mechanisms in L2 semantic processing.

In models 3 (concerning L2 proficiency) and 4 (concerning L2 dominance), only the main effects of effector type and language were significant. There were no interactions between effector type and L2 proficiency or L2 dominance.

4. Experiment 2

Experiment 1 showed that participants were slower to determine whether a picture semantically matched a preceding verb when the verb–picture pairs represented two distinct actions using the same effector, compared to when the actions involved different effectors. However, using visual pictures in Experiment 1 introduced a potential confound due to their inherent visual properties. One possibility is that participants' slower responses to actions involving the same effector demonstrated the picture's visual similarity rather than motor property activation (Bergen et al., 2010). Moreover, the task involved matching pictures with verbs, potentially prompting visual imagery instead of purely linguistic processing. Participants might consciously employ visual strategies in response to the picture stimuli, thereby leading to the observed effects. Experiment 2 addressed these issues by using written verbs instead of pictures and modifying the task to involve semantic relatedness judgments, including verb pairs without obvious effector-related information as fillers. These changes aimed to clarify whether the observed effects stemmed from the automatic activation of motor information during semantic comprehension.

4.1. Method

4.1.1. Participants

The same group of participants in Experiment 1 completed the semantic-relatedness judgment task in Experiment 2.

4.1.2. Design and stimuli

Similar to Experiment 1, we manipulated two independent variables: language (L1 and L2) and effector type (semantic-related same-effector, semantic-unrelated same-effector and semantic-unrelated different-effector)[6]. We focused on the participants' responses to the same and different effectors in the semantic-unrelated conditions and therefore employed a 2 (Language: L1, L2) × 2 (Effector type: same-effector, different-effector) within-participant design. Moreover, we incorporated L2 AoA, L2 proficiency,

[3]Interactions of three variables were not included as fixed effects in models 3 and 4 because they cannot improve model fit.

[4]Here and subsequently, we identified the significant interval using the Johnson–Neyman approach (Bauer & Curran, 2005), determining where simple slopes are significant in interaction contexts of regression models. This approach is particularly suitable when an interaction involves continuous variables, and could provide significant intervals without dichotomizing the continuous data.

[5]Here and subsequently, we identified the significant interval for using the Johnson–Neyman approach (Bauer & Curran, 2005).

[6]The semantic-related different-effector sub-condition was unavailable due to the rarity of two verbs that meet both criteria simultaneously.

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Table 4. Summary of the model results for Experiments 1 and 2

	Experiment 1			Experiment 2		
Fixed effects	*β*	*SE*	*t*	*β*	*SE*	*t*
Model 1: concerning L2 AoA						
(Intercept)	6.52	0.09	75.49***	6.58	0.09	76.21***
Effector type	0.12	0.03	3.92***	0.15	0.03	5.27***
Language	0.03	0.08	0.37	0.20	0.05	4.09***
L2 AoA	0.01	0.01	0.53	0.00	0.01	0.04
Effector type × Language	0.12	0.05	2.39*	0.09	0.05	1.70
Effector type × L2 AoA	−0.01	0.01	−2.33*	−0.01	0.01	−3.55***
Language × L2 AoA	0.01	0.01	0.43	−0.00	0.01	−0.16
Effector type × Language × L2 AoA	−0.02	0.01	−2.49*	−0.01	0.01	−2.07*
Model 2: concerning L2 exposure						
(Intercept)	6.58	0.13	48.76***	6.59	0.16	41.55***
Effector type	−0.05	0.04	−1.16	−0.13	0.05	−2.58*
Language	0.20	0.13	1.51	0.24	0.09	2.70**
L2 exposure	−0.02	0.22	−0.09	−0.02	0.25	−0.08
Effector type × Language	−0.21	0.08	−2.59**	−0.22	0.09	−2.19*
Effector type × L2 exposure	0.18	0.06	2.78**	0.30	0.08	4.00***
Language × L2 exposure	−0.21	0.21	−1.02	−0.07	0.14	−0.54
Effector type × Language × L2 exposure	0.33	0.13	2.60**	0.32	0.15	2.11*
Model 3: concerning L2 proficiency						
(Intercept)	6.67	0.12	57.84***	6.84	0.12	54.73***
Effector type	0.06	0.02	3.53***	0.07	0.01	5.44***
Language	0.07	0.02	3.33**	0.19	0.01	13.68***
L2 proficiency	−0.16	0.18	−0.88	−0.40	0.19	−2.09*
Model 4: concerning L2 dominance						
(Intercept)	6.75	0.12	56.31***	6.91	0.14	50.14***
Effector type	0.06	0.02	3.53***	0.07	0.01	5.44***
Language	0.07	0.02	3.32**	0.19	0.01	13.68***
L2 dominance	−0.26	0.17	−1.58	−0.45	0.19	−2.41*

Note: $^*p < .05$, $^{**}p < .01$, $^{***}p < .001$.

L2 exposure, and L2 dominance as continuous variables measuring different dimensions of bilingual experiences.

Table 5 illustrates the samples of experimental materials in Experiment 2, which involved a semantic relatedness judgment task with successive presentation of two verbs. Participants judged whether the target verb was semantically related to the preceding verb in Chinese and English blocks. Each language block comprised 100 verb–verb pairs with effectors (critical trials) and 100 verb–verb pairs without effectors (filler trials). Specifically, critical trials included 50 semantic-related pairs (e.g., flee–escape) and 50 semantic-unrelated pairs, equally divided between same-effector (e.g., swallow–whisper) and different-effector (e.g., applaud–stroll) trials. Likewise, filler trials featured semantically related (e.g., blend–merge) and unrelated (e.g., crack–fade) pairs. All trials were presented in a pseudorandom sequence. Our primary interest is to compare the semantic-unrelated pairs with the same effector versus those with different effectors during L1 and L2 processing.

Twenty participants (from the same university as our participants but did not participate in the experiments) rated the verbs' familiarity, imageability, concreteness, and degree of effector involvement on a 7-point scale. Chinese and English verb frequencies were derived from the frequency dictionaries by Cai and Brysbaert (2010) and Brysbaert and New (2009). All the verbs were high-frequent words (Chinese: $M = 1660.30$, $SD = 570.46$; English: $M = 100.43$, $SD = 208.18$). These frequencies, strokes of Chinese verbs, and word length of English verbs matched across different conditions (see Table S5 in the Supplementary Material).

4.1.3. Procedure

Experiment 2 followed a procedure akin to Experiment 1. Participants completed Chinese and English blocks in a counterbalanced sequence. Their task involved judging the semantic relatedness of visually presented verb pairs (Figure S1). Each trial began with a 500-ms black fixation cross, followed by a prime verb lasting

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Table 5. Sample stimuli of Experiment 2

Languages		Effector type	Prime verb	Target verb
L1: Chinese	Semantic-related	Same-effector (50) Filler (50)	逃跑 混合	逃走 融合
	Semantic-unrelated	Same-effector (25) Different-effector (25) Filler (50)	吞咽 鼓掌 裂开	私语 漫步 褪色
L2: English	Semantic-related	Same-effector (50) Filler (50)	flee blend	escape merge
	Semantic-unrelated	Same-effector (25) Different-effector (25) Filler (50)	swallow applaud crack	whisper stroll fade

Note: The Chinese prime and target words used in the experiment correspond to the English words. The numbers in parentheses following each effector type indicate the number of verb–verb pairs.

1500 ms, then a 500-ms blank interval. Subsequently, participants viewed the target verb for a maximum of 2000 ms or until they responded. They were instructed to press the Yes/No buttons accurately and promptly to indicate whether the target verb was semantically related to the preceding one, with button assignments counterbalanced across participants. RTs and accuracy data were collected.

4.2. Data analysis and results

We excluded 10 participants' data due to their low accuracy rates (<70%), leaving a final sample of 51 participants (mean age: 22 ± 1.86 years). Table S6 details the remaining participants' backgrounds. Incorrect responses (7.66%), outliers (M ± 3 SDs) of RT data (0.78%), and filler trials were eliminated from the analysis. We focused solely on the semantic-unrelated trials involving the same and different effectors for analysis. Table 3 provides the descriptive results.

4.2.1. L2 embodiment effect

Following the same modeling procedure (the basic model) in Experiment 1, we put log-transformed RT into an LME, with language (L1 and L2), effector type (same-effector and different-effector), and their interactions as fixed effects. Random effects included by-participant and by-item random intercepts, and by-participant and by-item random slopes for Language. We removed terms accounting for the least variance in the random effects structure from the model. Language and effector type were contrast-coded (L1 = −0.5, L2 = 0.5; different-effector = −0.5, same-effector = 0.5).

Figure 3A illustrates the RTs from the semantic relatedness judgment task. The main effect of the effector type was significant ($\beta = 0.06$, $SE = 0.01$, $t = 4.43$, $p < .001$). Figure 3A and Table 3 show that participants responded more slowly to the same-effector sub-condition (M = 779 ± 242 ms) compared to the different-effector sub-condition (M = 728 ± 212 ms). The main effect of language was significant as well ($\beta = 0.19$, $SE = 0.01$, $t = 13.63$, $p < .001$), reflecting faster responses in L1 (M = 681 ± 203 ms) than in L2 (M = 825 ± 251 ms). The interaction between language and effector type did not reach significance ($\beta = -0.012$, $SE = 0.02$, $t = -0.62$, $p = .54$). Further examination of the main effect of effector type for L1 and L2 revealed that semantic comprehension of action-related verbs was embodied in both L1 ($\beta = -0.07$, $SE = 0.01$, $t = -5.28$, $p < .0001$) and L2 ($\beta = -0.06$, $SE = 0.02$, $t = -2.91$, $p < .01$).

4.2.2. Correlations between bilingual experience and L2 embodiment

We investigated whether and how bilingual experience interacts with the L2 embodiment by correlating the four dimensions of bilingual experience with the L2 embodiment effect. Figure 3B displays the significant correlations between L2 AoA, L2 exposure, and L2 dominance with the L2 embodiment effect. The L2 proficiency correlation yielded null results, consistent with findings from Experiment 1.

4.2.3. Modulation effect of bilingual experience

To further investigate how bilingual experience modulates the L2 embodiment, similar to Experiment 1, we added each dimension of bilingual experiences one at a time to the prior basic mixed-effects model, constructing four separate models. Each model included language, effector type, one dimension of bilingual experiences and their interactions[7] as fixed effects. When the maximal random effects structure cannot converge, we iteratively streamlined the random effect structure until achieving convergence. The final models left by-participant and by-item random intercepts, and by-participant and by-item random slopes for language as the best-fitting random effects structure. Table 4 summarizes the results of the four models. We mainly focused on the interactions between the effector type (same-effector vs. different-effector) and the four dimensions. We analyzed these interactions through the releveling/nested effects.

In model 1 (concerning L2 AoA), we found a significant two-way interaction between the effector type and L2 AoA. Critically, a three-way interaction among effector type, language and L2 AoA was also significant. Follow-up analysis for the three-way interaction showed a significant Effector type × L2 AoA interaction ($\beta = -0.02$, $SE = 0.005$, $t = -3.85$, $p < .001$) in L2 processing (Figure 4), but not in L1 ($\beta = -0.005$, $SE = 0.005$, $t = -1.07$, $p = .28$). Specifically, the L2 embodiment effect occurred for L2 AoA before 8.4 years old but disappeared after that. Additionally, the nonsignificant Effector type × Language interaction (when L2 AoA was before 8.4) implied that L2 processing engages the sensorimotor system to a similar extent as L1 when one learned an L2 earlier in life.

In model 2 (concerning L2 exposure), the three-way interaction between effector type, language, and L2 exposure was significant. Follow-up analysis showed a significant Effector type × L2 exposure interaction ($\beta = 0.46$, $SE = 0.11$, $t = 4.20$, $p < .001$) in L2 processing (Figure 4), but not in L1 ($\beta = 0.14$, $SE = 0.10$, $t = 1.36$, $p = .18$). Specifically, the L2 embodiment effect was present when L2 exposure ranged from 0.61 to 0.80, but disappeared at lower levels (0.48–0.61). Moreover, the nonsignificant Effector type × Language interaction (when L2 exposure was beyond 0.61) indicated that bilinguals engage the sensorimotor system similarly in L2 as in L1 when sufficiently exposed to an L2. We further performed a principal component regression analysis to explore the individual contributions of the four dimensions to the L2 embodiment effect. Results highlighted that L2 exposure had the greatest relative impact (see supplementary Text 2, Tables S7 and S8 and Figure S3 for details), underscoring its crucial role in the embodiment of L2 semantic processing.

In models 3 (concerning L2 proficiency) and 4 (concerning L2 dominance), we found significant main effects for effector type and

[7]Interactions of three variables were not included as fixed effects in models 3 and 4 because they cannot improve model fit.

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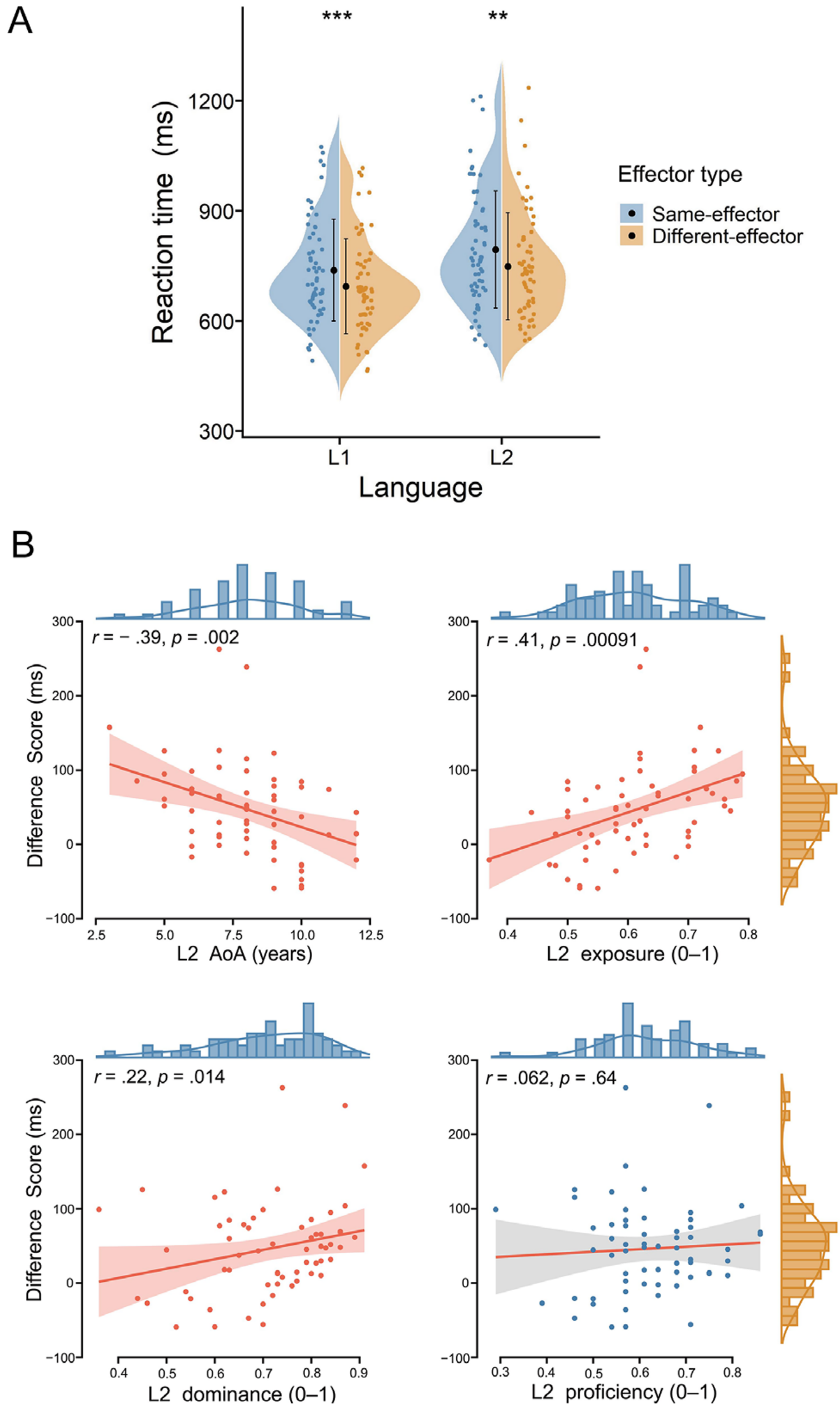

Figure 1. (A) Split violin plots showing the RTs of the verb–picture matching task (Experiment 1) in L1 and L2 across different effector types. The black dots show the mean value, and the vertical black lines represent the standard deviation. Asterisks indicate the significance level (**$p < .01$, ***$p < .001$). (B) Correlational relationships between L2 AoA, L2 exposure, L2 dominance, L2 proficiency, and the L2 embodiment effect (difference score = $RT_{same\text{-}effector} - RT_{different\text{-}effector}$). Smooth bands represent 95% confidence intervals (the gray band in the bottom-right line graph signifies no statistical significance). Additional histograms in the margins show the distribution of the data.

language, as well as for L2 proficiency and L2 dominance. There were no interactions between effector type and L2 proficiency or L2 dominance.

In addition, in both Experiments 1 and 2, we analyzed the influence of specific effectors (foot, hand, and mouth) on participants' response times by adding the effector as an additional

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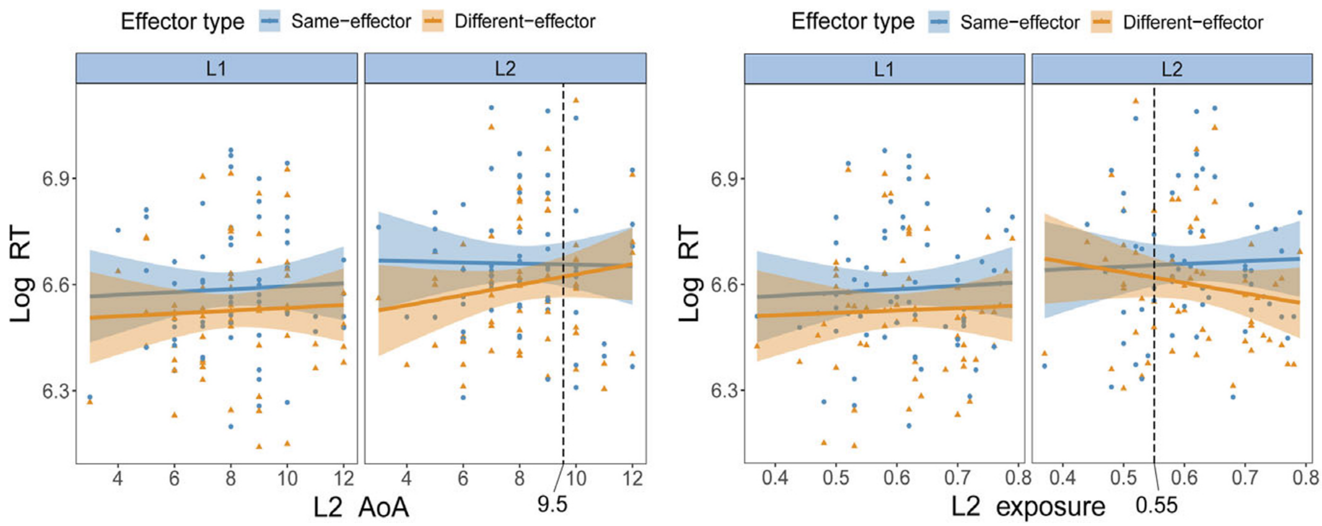

Figure 2. Interaction results in Experiment 1. Left: The interaction of L2 AoA with Effector type and Language. Smooth bands represent 95% confidence intervals. The vertical dashed line in the right panel indicates the critical value of L2 AoA for L2 embodiment. Right: The interaction of L2 exposure with Effector type and Language. Smooth bands represent 95% confidence intervals. The vertical dashed line in the right panel indicates the critical value of L2 exposure for L2 embodiment.

covariate in the LME model. Table S9 shows that effector variations did not significantly affect participants' responses. These findings are specific to our current behavioral data investigation. Future research might explore effector effects using neural methods like EEG or fMRI for more nuanced insights.

Furthermore, as the same participants performed in both experiments, we conducted a repeated measures omnibus analysis, integrating data from both experiments by including "experiment" as a variable in our LME models. The results from the best-fitted model (see Table S10) showed no significant main effect of the experiment, suggesting no obvious differences between the two. Besides, given that the two experiments primarily differed in stimulus modality (words vs. pictures), this finding indicates no significant effect of representation between these modalities in the context of the current study. Future research should further explore how different modalities of representation affect embodiment mechanisms.

To recapitulate, Experiment 2 replicated the findings of Experiment 1, confirming that the embodiment effect existed in both L1 and L2. Moreover, L2 AoA, L2 exposure, and L2 dominance correlated with the L2 embodiment effect, with the strength of this effect modulated by the level of L2 AoA and L2 exposure.

5. Discussion

This study investigated how and to what extent the spectrum of bilingual experience influences the L2 embodiment. We confirmed the involvement of the sensorimotor system in L2 semantic processing among Chinese–English bilinguals by examining participants' effector-specific responses to mismatched verb–picture pairs (Experiment 1) and semantically unrelated verb–verb pairs (Experiment 2). Meanwhile, using a continuous measurement approach, we quantified various dimensions of bilingual experience and observed that sensorimotor engagement varied as a function of L2 AoA and L2 exposure. These findings offer empirical support for embodied cognition theory in L2 contexts and enhance our understanding of how L2 embodiment interacts with bilingualism.

5.1. L2 embodiment effect

Our study initially investigated whether L2 semantic processing utilizes sensorimotor resources by manipulating effector information embedded in action verbs. As predicted, Chinese–English bilinguals exhibited slower response times to mismatched pairs in Experiment 1 (verb–picture) and semantic-unrelated pairs in Experiment 2 (verb–verb) when the pairs shared the same effector. This outcome reflects a general embodiment of L2 processing and reveals a complex interplay between semantic and sensorimotor processes.

Our findings support the hypothesis that L2 action semantics are grounded in sensorimotor experiences, as evidenced by the increased response times for same-effector pairs. Cognitively, participants tended to incorrectly respond with "yes" to verb–picture/verb pairs sharing an effector, whether perceptually or physically. This inclination may stem from the greater perceived resemblance of same-effector pairs compared to different-effector pairs, particularly when their semantic representations are anchored in multimodal experiences. Consequently, participants needed more time to accurately reject these same-effector pairs with a "no" response. This effector-specific response pattern suggests that L2 learners' semantic representations are influenced by sensorimotor experiences associated with the action semantics, compatible with the embodied cognition framework.

Further, the cognitive mechanisms underlying L2 embodiment may be linked to bilingual experience. Participants with richer learning experiences, such as early L2 acquisition and abundant L2 exposure, demonstrated a stronger embodiment effect as opposed to those with less extensive L2 learning experiences, indicating that their semantic systems are more tightly coupled with sensorimotor information (Ahn & Jiang, 2018; Buccino et al., 2017). Additionally, the influence of bilingual experience on L2 embodiment at the behavioral level supports the concept of structural and functional plasticity in neural systems (De Grauwe et al., 2014; Zhang et al., 2020). Extensive L2 learning experiences likely shape the neural substrates of semantic and sensorimotor processes (Pliatsikas et al., 2020), potentially accounting for the observed differences in response times for same-effector pairs in our experiments.

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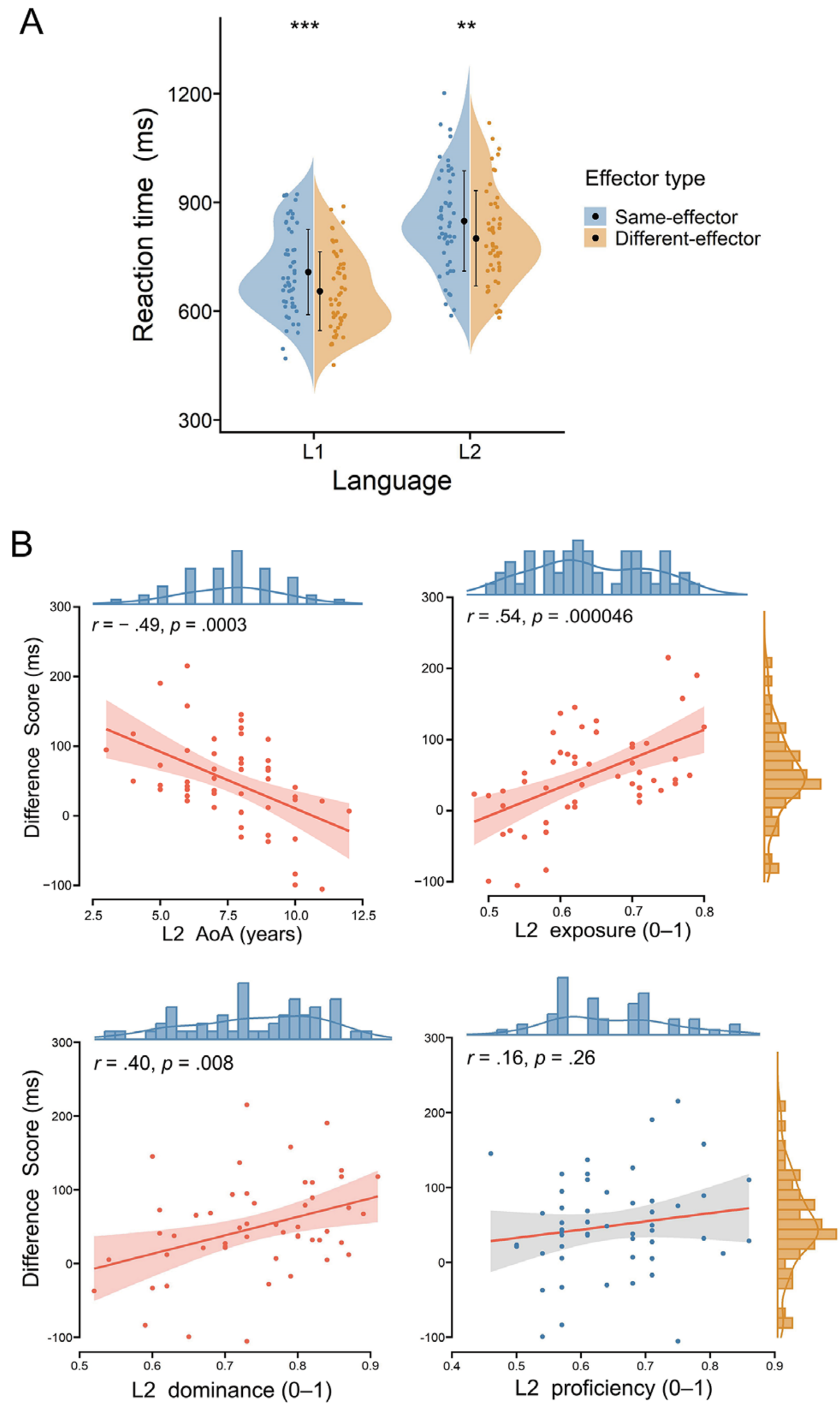

Figure 3. (A) Split violin plots showing the RTs of the semantic relatedness judgment task (Experiment 2) in L1 and L2 across different effector types. The black dots show the mean value, and the vertical black lines represent the standard deviation. Asterisks indicate the significance level (**$p < .01$, ***$p < .001$). (B) Correlational relationships between L2 AoA, L2 exposure, L2 dominance, L2 proficiency, and the L2 embodiment effect (difference score = $RT_{same\text{-}effector} - RT_{different\text{-}effector}$). Smooth bands represent 95% confidence intervals (the gray band in the bottom-right line graph signifies no statistical significance). Additional histograms in the margins show the distribution of the data.

Overall, the present study corroborates the role of sensorimotor networks in L2 processing. This result aligns well with previous studies (Ahlberg et al., 2017; Ahn & Jiang, 2018; Bergen et al., 2010; Buccino et al., 2017; Dudschig et al., 2014; Vukovic & Shtyrov, 2014), though some studies did not observe the embodiment effect in L2, in which, as noted earlier, facilitation effects (e.g., detected

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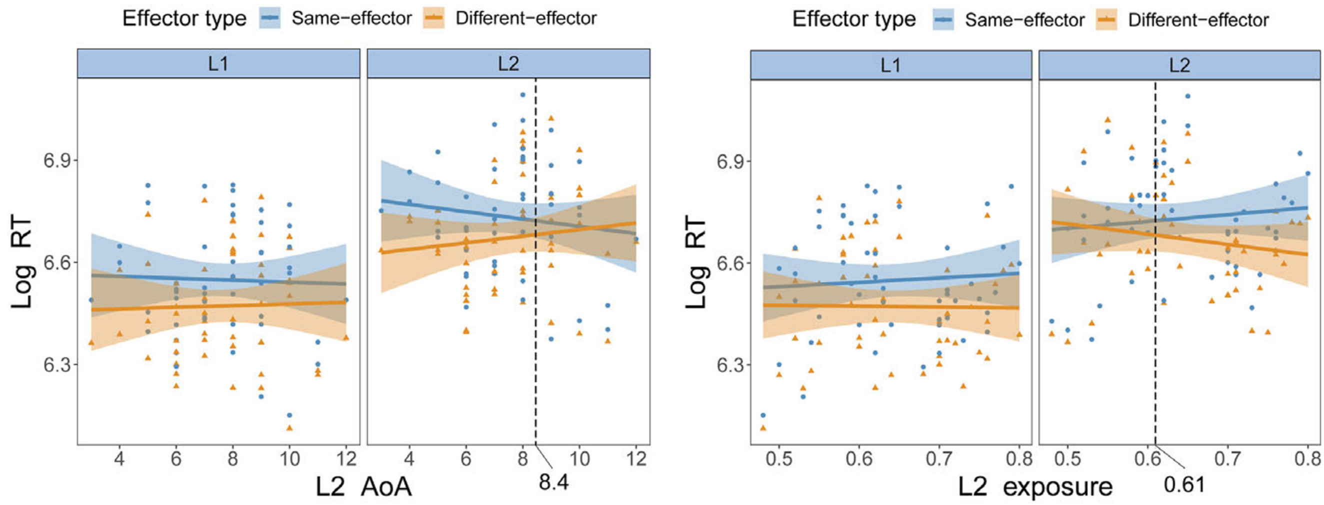

Figure 4. Interaction results in Experiment 2. Left: The interaction of L2 AoA with Effector type and Language. Smooth bands represent 95% confidence intervals. The vertical dashed line in the right panel indicates the critical value of L2 AoA for L2 embodiment. Right: The interaction of L2 exposure with Effector type and Language. Smooth bands represent 95% confidence intervals. The vertical dashed line in the right panel indicates the critical value of L2 exposure for L2 embodiment.

using the ACE paradigm in Morey et al., 2021 and the SPV task in Chen et al., 2020; Norman & Peleg, 2022) were taken as signs of the embodiment effect. Drawing methodological insights from prior literature (Shebani & Pulvermüller, 2013; Ostarek & Huettig, 2019), our study alternatively used interference effects as an embodiment proxy, potentially offering more compelling evidence than facilitation. Specifically, the interference effect occurs when responding to mismatched or semantic-unrelated pairs describing similar but incompatible actions (same-effector pairs), which simultaneously recruits incongruent motor systems responsible for particular actions. Then stronger mutual inhibition that emerges from actions involving the same effector compared to different effectors (Bergen et al., 2010; Ostarek & Huettig, 2019) likely interferes with participants' responses, leading to longer response times for same-effector pairs. This interference suggests a functional role of the sensorimotor system in L2 processing (Bergen, 2008; Bergen et al., 2010; Ostarek & Bottini, 2021), where the need to resolve this inhibition results in delayed response to fully discern verb meanings and correctly make "no" responses. Thus, motor system recruitment is crucial for action-related verb comprehension. Otherwise, effector information cannot modulate response times, and no differences would emerge between the same- and different-effector pairs.

Notably, the observed embodiment effect in our study specifically pertained to action verbs. Further investigation should clarify how this embodied mechanism influences the processing of abstract concepts and modulates L2 syntactic processing. Moreover, in Experiments 1 and 2, we counterbalanced the order of language blocks (L1 first or L2 first) and found no significant effects of language order, though prior research (e.g., Norman & Peleg, 2022) noted language order effects in visual simulations during SPV tasks. This discrepancy suggests a nuanced relationship between language order and embodiment effects in bilingual comprehension tasks, necessitating additional examination.

5.2. The role of bilingual experience in L2 embodiment

This study further explored how bilingual experience modulates L2 embodiment and revealed the relativity of L2 embodiment. We adopted a continuous assessment to characterize bilingual experience, indexed by L2 AoA, L2 exposure, L2 proficiency and L2 dominance. The observed results are consistent with the hypothesis that individual bilingual experiences shape L2 embodiment. The following section will delineate their respective modulation effects on L2 embodiment.

First, our findings indicated a correlation between L2 embodiment and early L2 AoA, with the strength of this relationship modulated by L2 AoA. This observation aligns with previous studies (Caldwell-Harris et al., 2011; Norman & Peleg, 2022; Tang et al., 2023; for a review: Pavlenko, 2012), showing that late bilinguals process linguistic stimuli more semantically and less perceptually or emotionally. A delayed L2 AoA is typically associated with explicit learning methods commonly employed in traditional classroom settings through amodal instructions. Conversely, an early L2 AoA relates to more neural plasticity and implicit L2 learning via multimodal experiences, facilitating more effective modality-specific sensorimotor grounding and integration (Monaco et al., 2019).

However, the modulation role of L2 AoA still seems open to question. Some studies found that even processing artificial or lately-learned languages may hinge on modality-specific systems (Macedonia & Mueller, 2016; Macedonia et al., 2011; Vukovic & Shtyrov, 2019), seemingly incompatible with our findings. However, when probing deeper into the learning or training modes used in these studies, we found that most participants underwent training with specific action manipulation or observation during the initial word learning phase (e.g., Bechtold et al., 2019; Öttl et al., 2017). For instance, Öttl et al. (2017) trained participants to learn artificial words as labels for novel objects in an interactive manner. In the word learning phase, participants encountered novel objects presented in upper or lower visual fields and learned their labels through interactive engagement. Subsequently, in the testing phase, participants were tasked with matching word colors with upward or downward arm movements in a Stroop-like task. Results showed faster responses when the movement direction matched the word's referent location during the learning phase, suggesting a connection between words and sensorimotor experiences. Notably, the acquisition context of these newly learned words, characterized by an embodied nature, resembled an early L2 AoA, which might indirectly favor embodiment effects (Kogan et al., 2020b). In addition,

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researchers noted that embodiment effects for these newly-learned languages attenuated compared to L1. In contrast, our study found no significant distinctions between L2 and L1 embodiment when participants learned the L2 relatively early. Thus, an early L2 AoA remains crucial for the emergence of embodiment effects, especially for L2 learners in formal educational settings.

Furthermore, the line of the above reasoning prompts consideration that while early L2 AoA correlates with L2 embodiment effects, this correlation may exhibit nonlinearity. Bilinguals acquiring their L2 later in life may still process the language through embodied mechanisms, especially when the acquisition process involves interactive bodily experiences. Early L2 AoA may not be the sole determinant of L2 embodiment, and mediating factors, such as the context or mode of L2 learning (e.g., formal instruction vs. immersion), warrant further exploration, as Monaco et al. (2021) suggested.

Our analysis also revealed that L2 exposure correlated with and modulated the L2 embodiment effect. To our knowledge, language exposure has rarely been manipulated in previous studies on bilingualism and embodiment. Allegedly, it may be interrelated with AoA and proficiency. Here, our findings suggest that increased L2 exposure is directly proportional to the L2 embodiment effect. Furthermore, among the four dimensions examined, L2 exposure emerges as the most influential factor in fostering L2 embodiment. This observation is reminiscent of Hebbian learning, which posits that "what fires together wires together" (Hebb, 1949). According to the principle of Hebbian learning, our study suggests that recurrent exposure to action words alongside their corresponding motor information helps to strengthen semantic-sensorimotor associations underlying language embodiment (Pulvermüller, 2005). Sustained L2 exposure allows L2 conceptual representations to be more easily linked to real-world referents with less L1 mediation. Thus, the L2 embodiment effect varied as a function of L2 exposure. Nonetheless, these findings could serve as preliminary data, leaving open questions regarding why L2 exposure significantly contributes to L2 embodiment and the underlying mechanisms through which it subserves L2 semantic grounding. Future studies should delve into these areas, offering additional behavioral and neurological evidence.

The current study fortunately identified a correlation between L2 dominance and the L2 embodiment effect. However, despite the broad distribution of L2 dominance scores, no modulation role was evident in either experiment. So far, our understanding of how L2 dominance affects L2 embodiment remains limited owing to the scarcity of relevant research. In our investigation, participants primarily used their L2 in conventional classroom settings, lacking immersive and interactive language contexts. This limitation may undermine the potential impact of high levels of L2 dominance, resulting in a less pronounced modulation role of L2 dominance in sensorimotor resonance.

Moreover, unexpectedly, our study observed no significant modulation effects of L2 proficiency on L2 embodiment, consistent with several recent research findings (Chen et al., 2020; Kogan et al., 2020a; Monaco et al., 2023; Zhang et al., 2020). Reaching a definite conclusion on the role of L2 proficiency in embodiment proves challenging due to various factors. In our study, we attribute the absence of significant effects to the notion proposed in previous research, indicating that L2 proficiency primarily modulates bilingual language executive control (Bonfifieni et al., 2019; Xie, 2018) and attention networks (Dash et al., 2022; Tse & Altarriba, 2014; Xing & Yang, 2023). However, regarding sensorimotor grounding, L2 proficiency appears to have a relatively peripheral and less sensitive role compared to other dimensions, at least based on the current study's outcomes.

Altogether, conceptualizing bilingualism as a continuous and multifaceted phenomenon allows us to systematically disentangle the distinct roles of L2 AoA, exposure, dominance, and proficiency in L2 embodiment. However, caution is warranted when assessing the modulation role of a specific variable, as their interconnected nature makes it challenging to establish causal relationships and generalize findings to diverse bilingual populations (Marian & Hayakawa, 2021). This complexity underscores the potential benefit of a unified indicator, such as the "bilingualism quotient" proposed by Marian and Hayakawa (2021), which consolidates various components of bilingual experience into a single index.

As a whole, the current findings offer valuable insights into L2 embodiment, underscoring that its presence varies among bilinguals based on varying L2 learning experiences, such as the timing of L2 acquisition and the degree of L2 exposure (Claussenius-Kalman et al., 2021; DeLuca et al., 2020). In line with our hypothesis, early L2 acquisition and substantial L2 exposure are conducive to a more embodied approach to L2 processing, akin to L1 embodiment. In contrast, according to the dual-coding knowledge neural framework (Bi, 2021; Wang et al., 2020), which differentiates between sensory-derived (embodied) and language-derived (disembodied) concept representations, we speculate that late L2 acquisition and limited L2 exposure may correspond to a more symbolic and disembodied processing mechanism. This hypothesis is corroborated by Momenian et al. (2021), who demonstrated that bilinguals with less L2 experience rely more on symbolic-based mechanisms in action word processing. Crucially, the above analysis implies that L2 semantic processing is not solely embodied or completely disembodied, reinforcing Willems and Francken's (2012) call for a reevaluation of embodied cognition by transcending binary distinctions and developing more nuanced theories of bilingualism-induced L2 embodiment.

5.3. Limitations and future studies

The current study has several limitations that merit further investigation. First, the relationship between symbolic and embodied semantic representations in L2 processing remains unclear, as our assumption of their coexistence has not received empirical confirmation. Future research agendas should aim to develop a unified notion considering both forms and addressing questions such as their integration or separation, functional roles and developmental trajectories underlying the dynamics of bilingual experience (Bi, 2021). Second, our study mainly investigated the linear relationship between bilingual experience and L2 embodiment. While we controlled for additional variables (e.g., L2 learning context and mode) across participants, these variables may moderate the factors examined. Future research should endeavor to investigate nonlinear relationships with these mediating variables factored into the experimental design. Third, our study represented the first attempt to explore the impacts of multiple dimensions of bilingual experience on L2 embodiment, with the results confined to their respective contributions. Upcoming research could explore the interrelationships between these dimensions and their combined effects on L2 embodiment. Finally, our sample of participants is relatively homogeneous with less varied L2 experiences. Nevertheless, we also observed a pronounced effect of L2 exposure. Encompassing a more diverse range of participants would enhance the generalizability of our findings and advance the understanding of L2 embodiment. Besides, from a practical perspective, future

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investigations can incorporate embodied insights into L2 acquisition models, such as grounding L2 learning in social interaction (Li & Jeong, 2020) and utilizing immersive technologies like virtual reality (Legault et al., 2019; Li et al., 2020) to facilitate L2 learning and teaching.

6. Conclusion

In conclusion, our findings highlight the significant impact of bilingual experience, characterized as a multifaceted and continuous phenomenon, on L2-embodied semantic systems. Early and substantial exposure to an L2 correlates with the increased recruitment of these systems, with L2 exposure emerging as the most influential factor. Our study responds to recent calls for a nuanced understanding of bilingualism as a multidimensional spectrum and sheds light on the relative L2 embodiment modulated by bilingual experience. Crucially, our evidence weighs against the simplistic dichotomy of L2 processing as purely embodied or disembodied, introducing fresh insights into the dual nature of L2 semantic representations and offering promising avenues for enhancing L2 learning and teaching strategies.

Supplementary material. To view supplementary material for this article, please visit http://doi.org/10.1017/S1366728924000981.

Data availability statement. The data supporting this study's findings are openly available in OSF at https://osf.io/zqp8b/.

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Competing interest. The authors have no conflicts of interest to declare.

References

Ahlberg, D. K., Bischoff, H., Kaup, B., Bryant, D., & Strozyk, J. V. (2017). Grounded cognition: Comparing Language × Space interactions in first language and second language. *Applied Psycholinguistics*, **39**(2), 437–459.

Anderson, A. J., Binder, J. R., Fernandino, L., Humphries, C. J., Conant, L. L., Raizada, R. D. S., Lin, F., & Lalor, E. C. (2019). An integrated neural decoder of linguistic and experiential meaning. *Journal of Neuroscience*, **39**(45), 8969–8987.

Ahn, S., & Jiang, N. (2018) Automatic semantic integration during L2 sentential reading. Bilingualism: Language and Cognition, **21**, 375–383.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, **59**, 617–645.

Bergen, B. (2008). Experimental methods for simulation semantics. In M. Gonzalez-Marquez, I. Mittelberg, S. Coulson, & M. Spivey (Eds.), *Methods in cognitive linguistics* (pp. 277–301). Amsterdam: Benjamins.

Bergen, B., Lau, T.-T. C., Narayan, S., Stojanovic, D., & Wheeler, K. (2010). Body part representations in verbal semantics. *Memory and Cognition*, **38**(7), 969–981.

Binder, J. R. (2016). In defense of abstract conceptual representations. *Psychonomic Bulletin and Review*, **23**, 1096–1108.

Bi Y. (2021). Dual coding of knowledge in the human brain. *Trends in Cognitive Sciences*, **25**(10), 883–895.

Bonfifieni, M., Branigan, H. P., Pickering, M. J., & Sorace, A. (2019). Language experience modulates bilingual language control: The effect of proficiency, age of acquisition, and exposure on language switching. *Acta Psychologica*, **193**, 160–170.

Birba, A., Beltrán, D., Caro, M. M., Trevisan, P., Kogan, B., Sedeño, L., Ibáñez, A., & García, A. M. (2020). Motor-system dynamics during naturalistic reading of action narratives in first and second language. *NeuroImage*, **216**, 1–11.

Bauer, D. J., & Curran, P. J. (2005). Probing interactions in fixed and multilevel regression: Inferential and graphical techniques. *Multivariate Behavioral Research*, **40**(3), 373–400.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, **68**(3), 255–278.

Bechtold, L., Ghio, M., Antoch, G., Turowski, B., Wittsack, H.-J., Tettamanti, M., & Bellebaum, C. (2019). How words get meaning: The neural processing of novel object names after sensorimotor training. *NeuroImage*, **197**, 284–294.

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-efects models using lme4. *Journal of Statistical Software*, **67**(1), 1–48.

Buccino, G., Colagè, I., Gobbi, N., & Bonaccorso, G. (2016). Grounding meaning in experience: A broad perspective on embodied language. *Neuroscience and Biobehavioral Reviews*, **69**, 69–78.

Buccino, G., Marino, B. F., Bulgarelli, C., & Mezzadri, M. (2017). Fluent speakers of a second language process graspable nouns expressed in L2 like in their native language. *Frontiers in Psychology*, **8**, 2–8.

Brysbaert, M., & New, B. (2009). Moving beyond KuČera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, **41**(4), 977–990.

Cai, Q., & Brysbaert, M. (2010). SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *Plos One*, **5**(6), 1–8.

Claussenius-Kalman, H., Hernandez, A. E., Li, P. (2021). Expertise, ecosystem, and emergentism: Dynamic developmental bilingualism. *Brain and Language*, **222**, 1–8.

Caldwell-Harris, C., Tong, J., Lung, W., & Poo, S. (2011). Physiological reactivity to emotional phrases in Mandarin-English bilinguals. *International Journal of Bilingualism*, **15**, 329–352.

Chen, D., Wang, R., Zhang, J., & Liu, C. (2020). Perceptual representations in L1, L2 and L3 comprehension: delayed sentence–picture verification. *Journal of Psycholinguistic Research*, **49**(1), 41–57.

de Bruin, A. (2019). Not all bilinguals are the same: A call for more detailed assessments and descriptions of bilingual experiences. *Behavioral Sciences*, **9**(3), 1–13.

Dewaele, J.-M. (2010). *Emotions in multiple languages*. London: Palgrave Macmillan.

Dash, T., Joanette, Y., & Ansaldo, A. I. (2022). Exploring attention in the bilingualism continuum: A resting-state functional connectivity study. *Brain and Language*, **224**, 1–11.

Dudschig, C., de la Vega, I., & Kaup, B. (2014). Embodiment and second-language: Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm. *Brain and Language*, **132**, 14–21.

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, **116** (15), 7565–7574.

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage*, **204**, 2–11.

De Grauwe, S., Willems, R. M., Rueschemeyer, S. A., Lemhofer, K., Schriefers, H. (2014). Embodied language in first- and second-language speakers: Neural correlates of processing motor verbs. Neuropsychologia, **56**, 334–349.

Fodor, J. A. (1975). *The language of thought*. New York: Crowell.

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *Quarterly Journal of Experimental Psychology*, **61**(6), 825–850.

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., Klein, D., Baum, S., Phillips, N., & Titone, D. (2021). Bilingual language experience as a multidimensional spectrum: Associations with objective and subjective language proficiency. *Applied Psycholinguistics*, **42**, 245–278.

Glenberg, A. M., & **Kaschak, M. P.** (2002). Grounding language in action. *Psychonomic Bulletin and Review*, **9**(3), 558–565.

Gu, B., **Wang, H.**, **Beltrán, D.**, **Liu, B.**, **Liang, T.**, **Wang, X.**, & **de Vega, M.** (2021). Embodied processing of disgust in Mandarin words: An ERP study. *Journal of Neurolinguistics*, **58**, 2–11.

Hebb, D. O. (1949). *The organization of behavior*. Hoboken, NJ: John Wiley & Sons.

Hauk, O., **Johnsrude, I.**, & **Pulvermüller, F.** (2004). Somatopic representation of action words in human motor and premotor cortex. *Neuron*, **41**, 301–307.

Jeong, H., **Li, P.**, **Suzuki, W.**, **Sugiura, M.**, & **Kawashima, R.** (2021). Neural mechanisms of language learning from social contexts. *Brain and Language*, **212**, 1–12.

Johari, K., **Riccardi, N.**, **Malyutina, S.**, **Modi, M.**, & **Desai, R. H.** (2022). HD-tDCS of primary and higher-order motor cortex affects action word processing. *Frontiers in Human Neuroscience*, **16**, 1–12.

Kuznetsova, A., **Brockhoff, P. B.**, & **Christensen, R. H. B.** (2017). lmertest package: Tests in linear mixed effects models. *Journal of Statistical Software*, **82**(13), 1–26.

Kühne, K., & **Gianelli, C.** (2019). Is embodied cognition bilingual? Current evidence and perspectives of the embodied cognition approach to bilingual language processing. *Frontiers in Psychology*, **10**, 1–8.

Kogan, B., **García-Marco, E.**, **Birba, A.**, **Cortés, C.**, **Melloni, M.**, **Ibáñez, A.**, et al. (2020a). How words ripple through bilingual hands: Motor–language coupling during L1 and L2 writing. *Neuropsychologia*, **146**, 2–9.

Kogan, B, **Muñoz, E**, **Ibáñez, A and García, A. M.** (2020b). Too late to be grounded? Motor resonance for action words acquired after middle childhood. *Brain and Cognition*, **138**, 1–19.

Klepp, A., **Weissler, H.**, **Niccolai, V.**, **Terhalle, A.**, **Geisler, H.**, **Schnitzler, A.**, & **Biermann-Ruben, K.** (2014). Neuromagnetic hand and foot motor sources recruited during action verb processing. *Brain and Language*, **128**(1), 41–52.

Luk, G., & **Bialystok, E.** (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *Journal of Cognitive Psychology*, **25** (5), 605–621.

Li, P., & **Dong, Y.** (2020). Language experiences and cognitive control: A dynamic perspective. In *Psychology of learning and motivation* (Vol. **72**, pp. 27–52). Elsevier.

Li, P., & **Jeong, H.** (2020). The social brain of language: Grounding second language learning in social interaction. *npj Science of Learning*, **5**(1), 1–9.

Li, P., **Legault, J.**, **Klippel, A.**, & **Zhao, J.** (2020). Virtual reality for student learning: Understanding individual differences. *Human Behaviour and Brain*, **1**(1), 28–36.

Li, P., **Zhang, F.**, **Yu, A.**, & **Zhao, X.** (2019). Language history questionnaire (LHQ3): An enhanced tool for assessing multilingual experience. *Bilingualism: Language and Cognition*, 1–7.

Li, J., **Zheng, Y.**, & **Yang, J.** (2018). The influence of second language proficiency on the automatic activation of Chinese during English lexical access in Chinese-English bilinguals. *Foreign Language Teaching and Research*, **50**(1), 101–113.

Legault, J., **Zhao, J.**, **Chi, Y-A.**, **Chen, W.**, **Klippel, A.**, & **Li, P.** (2019). Immersive virtual reality as an effective tool for second language vocabulary learning. *Languages*, **4**(1), 1–32.

Momenian, M., **Bakhtiar, M.**, **Chan, Y. K.**, **Cheung, S. L.**, & **Weekes, B. S.** (2021). Picture naming in bilingual and monolingual Chinese speakers: Capturing similarity and variability. *Behavior Research Methods*, **53**(4), 1677–1688.

Momenian, M., **Privitera, A. J.**, & **Weekes, B.** (2024). Nouns are not always processed faster than verbs in bilingual speakers: Effects of language distance. *Bilingualism: Language and Cognition*, **27**, 75–83.

Marian, V., & **Hayakawa, S.** (2021). Measuring bilingualism: The quest for a "bilingualism quotient". *Applied Psycholinguistics*, **42**, 527–548.

Monaco, E., **Jost, L. B.**, **Gygax, P. M.**, & **Annoni, J.-M.** (2019). Embodied Semantics in a Second Language: Critical Review and Clinical Implications. *Frontiers in Human Neuroscience*, **13**, 1–21.

Monaco, E., **Jost, L. B.**, **Lancheros, M.**, **Harquel, S.**, **Schmidlin, E.**, **Annoni, J-M.** (2021). First and second language at hand: A chronometric transcranial-magnetic stimulation study on semantic and motor resonance. *Journal of Cognitive Neuroscience*, **33**(8), 1563–1580.

Matuschek, H., **Kliegl, R.**, **Vasishth, S.**, **Baayen, H.**, & **Bates, D.** (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, **94**, 305–315.

Morey, R. D., **Kaschak, M. P.**, **Díez-Álamo, A. M.** et al. (2021). A pre-registered, multi-lab non-replication of the action-sentence compatibility effect (ACE). *Psychonomic Bulletin and Review*, **23**, 1096–1108.

Monaco, E., **Mouthon, M.**, **Britz, J.**, **Sato, S.**, **Stefanos-Yakoub, I.**, **Annoni, J. M.**, & **Jost, L. B.** (2023). Embodiment of action-related language in the native and a late foreign language – An fMRI-study. *Brain and Language*, **244**, 1–12.

Macedonia, M., & **Mueller, K.** (2016). Exploring the neural representation of novel words learned through enactment in a word recognition task. *Frontiers in Psychology*, **7**, 1–14.

Macedonia, M., **Muller, K.**, & **Friederici, A. D.** (2011). The impact of iconic gestures on foreign language word learning and its neural substrate. *Human Brain Mapping*, **32**(6), 982–998.

Montero-Melis, G., **van Paridon, J.**, **Ostarek, M.**, & **Bylund, E.** (2022). No evidence for embodiment: The motor system is not needed to keep action verbs in working memory, *Cortex*, **150**, 108–125.

Marino, B. F. M., **Sirianni, M.**, **Volta, R. D.**, **Magliocco, F.**, **Silipo, F.**, **Quattrone, A.**, & **Buccino, G.** (2014). Viewing photos and reading nouns of natural graspable objects similarly modulate motor responses. *Frontiers in Human Neuroscience*, **8**, 1–10.

Norman, T., & **Peleg, O.** (2022). The reduced embodiment of a second language. *Bilingualism: Language and Cognition*, **25**(3), 406–416.

Öttl, B., **Dudschig, C.**, & **Kaup, B.** (2017). Forming associations between language and sensorimotor traces during novel word learning. *Language and Cognition*, **9**(1), 156–171.

Ostarek, M., & **Huettig, F.** (2019). Six challenges for embodiment research. *Current Directions in Psychological Science*, **28**(6), 593–599.

Ostarek, M., & **Bottini, R.** (2021). Towards strong inference in research on embodiment – possibilities and limitations of casual paradigms. *Journal of Cognition*, **4**(1), 1–21.

Pylyshyn, Z. W. (1984). *Computation and cognition*. Cambridge, MA: MIT Press.

Pavlenko, A. (2012). Affective processing in bilingual speakers: Disembodied cognition? *International Journal of Psychology*, **47**(6), 405–428.

Pliatsikas, C., **DeLuca, V.**, & **Voits, T.** (2020). The many shades of Bilingualism: Language experiences modulate adaptations in brain structure. *Language Learning*, **70**(2), 133–149.

Pulvermüller, F., **Hauk, O.**, **Nikulin, V. V.**, & **Ilmoniemi, R.** (2005). Functional links between motor and language systems. *European Journal of Neuroscience*, **21**, 793–797.

Pulvermüller, F., & **Fadiga, L.** (2010). Active perception: Sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience*, **11**(5), 351–360.

R Core Team (2023). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing. https://www.R-project.org/

Shebani, Z., & **Pulvermüller, F.** (2013). Moving the hands and feet specifically impairs working memory for arm- and leg-related action words. *Cortex*, **49** (1), 222–231.

Shebani, Z., & **Pulvermüller, F.** (2018). Flexibility in language action interaction: The inflfluence of movement type. *Frontiers in Human Neuroscience*, **12**, 1–11.

Sato, M., **Schafer, A. J.**, & **Bergen B. K.** (2013). One word at a time: Mental representations of object shape change incrementally during sentence processing. *Language and Cognition*, **5**, 345–373.

Syndicate, U. C. L. E. (2001). *Quick placement test*. Oxford: Oxford University Press.

Treffers-Daller, J. (2019). What defines language dominance in bilinguals? *Annual Review of Linguistics*, **5**, 375–393.

Tse, C. S., & **Altarriba, J.** (2014). The relationship between language proficiency and attentional control in Cantonese-English bilingual children: Evidence from Simon, Simon switching, and working memory tasks. *Frontiers in Psychology*, **5**, 1–18.

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**, 273–281.

Tian, L., **Chen, H.**, **Zhao, W.**, **Wu, J.**, **Zhang, Q.**, **De, A.**, **Leppänen, P.**, **Cong, F.**, & **Parviainen, T.** (2020). The role of motor system in action-related language comprehension in L1 and L2: An fMRI study. *Brain and Language*, **201**, 1–12.

Tang, D., **Fu, Y.**, **Wang, H.**, **Liu, B.**, **Zang, A.**, & **Kärkkäinen, T.** (2023). The embodiment of emotion-label words and emotion-laden words: Evidence from late Chinese–English bilinguals. *Frontiers in Psychology*, **14**, 1–11.

Tsaregorodtseva, O., & **Kaup, B.** (2024). Experiential traces first: Does holding a location in visuospatial working memory affect the processing of space-associated words? *Memory and Cognition*, **52**, 965–983.

Treffers-Daller, J., & **Silva-Corvalán, C.** (eds.) (2015). *Language dominance in bilinguals: Issues of measurement and operationalization*. Cambridge: Cambridge University Press.

Vukovic, N. (2013). When words get physical: Evidence for proficiency-modulated somatotopic motor interference during second language comprehension. *Proceedings of the Annual Meeting of the Cognitive Science Society*, **35**, 3711–3716.

Vukovic, N., & **Shtyrov, Y.** (2014). Cortical motor systems are involved in second-language comprehension: Evidence from rapid mu-rhythm desynchronisation. *NeuroImage*, **102**, 695–703.

Vukovic, N., & **Shtyrov, Y.** (2019). Learning with the wave of the hand: Kinematic and TMS evidence of primary motor cortex role in category-specific encoding of word meaning. *NeuroImage*, **202**, 1–9.

von Sobbe, L., **Ulrich, R.**, **Gangloff, L.**, **Scheifele, E.**, **Maienborn, C**. (2021). Is rushing always faster than strolling? A reaction time study on the processing of sentences containing manner of motion verbs. *Acta Psychologica*, **221**, 1–14.

Winter, B., & **Bergen B.** (2012). Language comprehenders represent object distance both visually and auditorily. *Language and Cognition*, **4**, 1–16.

Winter, A., **Dudschig, C.**, **Miller, J.**, **Ulrich, R.**, & **Kaup, B.** (2022). The action-sentence compatibility effect (ACE): Meta-analysis of a benchmark finding for embodiment. *Acta Psychologica*, **230**, 1–15.

Wang, X., **Men, W.**, **Gao, J.**, **Caramazza, A.**, **Bi, Y.** (2020). Two forms of knowledge representations in the human brain. *Neuron*, **107**, 383–393.

Willems, R. M., & **Francken, J. C.** (2012). Embodied cognition: Taking the next step. *Frontiers in Psychology*, **3**, 1–3.

Xie, Z. (2018). The influence of second language (L2) proficiency on cognitive control among young adult unbalanced Chinese-English bilinguals. *Frontiers in Psychology*, **9**, 412–412.

Xing, S. J., & **Yang, J.** (2023). The Impact of interpreting training experience on the attentional networks and their dynamics. *Brain Sciences*, **13**, 1–16.

Yaxley, R. H., & **Zwaan, R. A.** (2007). Simulating visibility during language comprehension. *Cognition*, **105**, 229–236.

Zwaan, R. A., & **Pecher, D.** (2012). Revisiting mental simulation in language comprehension: Six replication attempts. *PLoS One*, **7**(12), 1–10.

Zeelenberg, R., & **Pecher, D.** (2016). The role of motor action in memory for objects and words. In H. B. Ross (Ed.), *Psychology of learning and motivation*, **64** (pp. 161–193). Academic Press.

Zhang, X., **Yang, J.**, **Wang, R.**, & **Li, P.** (2020). A neuroimaging study of semantic representation in first and second languages. *Language, Cognition and Neuroscience*, **35**(10), 1223–1238.

Zhang, C., **Zhang, H.**, **Zheng, X.**, & **Yang, J.** (2020). A comparative study of English proficiency testing in Chinese-English bilinguals. *Foreign Language Teaching and Research*, **52**(5), 701–712.