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Research Article

Mental simulation in bilingual and second language processing: New directions in the Competition Model☆

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1. Introduction

The seminal volume *Cognitive Processing in Bilinguals* (Harris, 1992) marked a key moment in the study of bilingual cognition, presenting foundational theories and studies that continue to inform and inspire research in the area three decades later. Among the influential contributions in this volume is the Competition Model (MacWhinney, 1987, 1992, 2021), a theory that provides a framework for understanding how bilinguals navigate the complex interplay of linguistic cues across their two languages. Grounded in principles of connectionism and functionalism, the Competition Model has elucidated mechanisms of transfer, cue competition, and functional restructuring in bilingual language processing.

At the heart of the Competition Model is the idea that multiple linguistic cues, such as word order, animacy, and case marking, compete for control during sentence processing, and the interpretation outcome depends on the relative strength, availability, and reliability of each cue within a speaker's cognitive system (MacWhinney, 2021). For instance, English speakers tend to prioritise word order as a reliable cue for thematic role assignment, whereas German speakers rely more heavily on case marking (MacWhinney et al., 1984). These crosslinguistic differences in cue weighting are explained by the notion of *cue validity*, defined as the product of cue availability and reliability. When acquiring a second language (L2), learners initially transfer L1 cue strengths, resulting in forward transfer effects during L2 sentence interpretation (Liu, Bates, & Li, 1992). Over time, with increased exposure to the L2, learners begin to reweight cues, adjusting to the statistical regularities of the target language. This gradual process of cue adjustment drives functional restructuring, wherein learners reorganize their form-function mappings and develop L2-specific processing strategies (Li & MacWhinney, 2013). Extensive empirical studies using reaction-time experiments, ERP data, and bilingual corpora support this adaptive mechanism and demonstrate how bilinguals shift from L1-dominant to more L2-aligned cue use (Tokowicz & MacWhinney, 2005; Chen, Shu, Liu, Zhao, & Li, 2007). Collectively, these findings underscore the cognitive flexibility that characterises bilingual language processing.

In parallel, advances in cognitive science, particularly in embodied cognition and mental simulation, offer new perspectives that complement and enrich the theoretical architecture of the Competition Model. Embodied cognition research emphasizes that language comprehension is grounded in sensorimotor systems and bodily experiences (Barsalou, 2010; Zwaan, 2008). A central mechanism within this framework is mental simulation, the process by which individuals internally reactivate perceptual and motor experiences to interpret linguistic input (Kaschak et al., 2014). MacWhinney's (1977, 2008) Perspective Hypothesis extends this notion and proposes that language comprehension involves running mental simulations that reproduce previously encoded sensorimotor experiences. This simulation process is supported by body part matching, which enables individuals to map the observed actions or sensations of others onto their own body schema, thereby activating corresponding neural pathways as if they were performing the actions themselves. This embodied process facilitates not only action understanding but also the construction of mental models, which are dynamic, integrated representations of spatial, temporal, emotional, and causal information. In MacWhinney's view, mental models are fundamentally perspectival and continuously updated through perspective tracking. Perspective tracking is the dynamic adoption and shifting of viewpoints, for instance, following the perspective of different characters in a narrative or tracking changes in the speaker's focus, to maintain a coherent and embodied representation of unfolding events. Language provides lexical, grammatical, and discourse cues that guide this perspectival integration and allow listeners to link experiences, actions, and emotions across time and participants within a shared mental space.

The processes of cue competition and mental model construction are

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linked together during real-time processing. During comprehension, cue comprehension works to assign roles to the referents described in the input. These assignments then work along with spatial descriptions and actions to build fleshed-out dynamic mental models organized from the perspective of one of the referents which then engages in action on the referents as specified by the verb. All of this occurs with a spatial and temporal setting depicted by other elements of the input utterance and discourse. In production, there is the inverse readout from mental models to referent characterization and grammatical role assignments to produce plans for utterances. A further characterization of this process will be given later.

Within second language acquisition (SLA), the embodiment of linguistic meaning has gained empirical support. Behavioural and neurophysiological studies indicate that L2 embodiment effects tend to be weaker than those in L1, particularly among late bilinguals whose L2 learning often occurs through explicit, decontextualized instruction with limited sensory engagement (Ahlberg et al., 2017; Baumeister et al., 2017; Qian, 2016). Nevertheless, sensorimotor embodiment in L2 processing remains measurable and appears to vary as a function of L2 proficiency (Bergen, Lau, Narayan, Stojanovic, & Wheeler, 2010; Monaco et al., 2019). Learners with higher proficiency tend to show stronger and more native-like activation of sensorimotor systems, suggesting that the mechanisms of cue reweighting and functional restructuring may extend beyond abstract linguistic features to include embodied dimensions of meaning. In this light, the Competition Model can be broadened to incorporate *sensorimotor cue validity* – the extent to which embodied experiences contribute to meaning construction in L2. This reconceptualisation positions embodied simulation as both a constraint and a resource in L2 learning, which affects how learners interpret cues, construct mental models, and integrate language with action and perception.

Building on this foundation, the current article explores how recent mental simulation research (Zhao, Vanek, Yang, & Wang, 2025) enriches the less-discussed notions of decoupling and functional restructuring within the Competition Model. Decoupling, or the ability to process and think in the L2 without reliance on the first language (L1) (Kroll, Van Hell, Tokowicz, & Green, 2010) emerges as a critical factor in understanding how bilinguals engage in mental simulations when each of their languages might modulate in different ways. Functional restructuring, the process by which bilinguals adapt and reconfigure cognitive systems to accommodate the demands of two languages (Vanek et al., 2024), is likewise illuminated by studies demonstrating how bilinguals' sensorimotor systems respond to the distinct affordances of their languages.

By revisiting the Competition Model through the lens of bilingual mental simulation research, this article aims to shed light on the evolution of its core concepts. This reflection not only celebrates the model's enduring contributions but also situates it within the broader trajectory of bilingualism research, offering insights into the dynamic interplay between linguistic structures, cognitive mechanisms, and embodied representations in bilingual language use.

2. Cue competition and L2 mental models

The Competition Model argues that language learning and processing rely on the interaction of cues – relationships between linguistic forms and their functions – across phonology, lexicon, and grammar. Cues are in constant competition in language processing. This competition is determined by *cue strength*, which is influenced by *cue* reliability (how accurately a cue predicts a function) and availability (how frequently a cue is encountered). Cue competition shapes how language learners process and produce language, with stronger cues having a higher likelihood of influencing comprehension and production. At the early stage of language acquisition, cue availability plays a more important role, but over time, cue reliability becomes the dominant factor (McDonald & Heilenman, 1991; Zhao & Fan, 2021).

Understanding cue competition is crucial to examining how L2 learners develop mental models for their second language. Studies such as Xue, Xie, Lu, Niu, and Marmolejo-Ramos (2024) illustrate how cue properties vary between L1 and L2 learning contexts. Xue et al. adopted a developmental perspective on embodied cognition and investigated how sensorimotor experiences interact with the age of acquisition (AoA) of concepts in bilinguals speaking L1 Chinese and L2 English. They collected sensorimotor ratings for 207 items, evaluating the extent to which these concepts were experienced through six sensory modalities (touch, hearing, smell, taste, vision, interoception) and five action effectors (foot/leg, hand/arm, head-minus-mouth, mouth/throat, torso). Data on AoA and word frequency for both languages was gathered as well. The analyses revealed that sensorimotor grounding and frequency compete in predicting the AoA of concepts. For L1 Chinese, sensorimotor experience was a stronger predictor of AoA after controlling for frequency, while for L2 English, frequency played a more dominant role. Regarding cue competition, this indicates that in L1 sensorimotor grounding and linguistic input co-occur as competing cues, with sensorimotor cues having a greater influence on processing and acquisition. In L2, however, linguistic input frequency dominates the competition, likely due to the formal learning context of L2 acquisition. As for cue strength, sensorimotor grounding in L1 Chinese explained more variance in AoA compared to its role in L2 English, suggesting that sensorimotor experiences are stronger cues in naturalistic L1 acquisition contexts. In contrast, L2 learners relied more heavily on frequency, demonstrating weaker cue strength of sensorimotor experiences in formal L2 learning environments. Regarding reliability, sensorimotor cues are arguably more reliable in L1 because they are grounded in direct interactions with the physical world during early childhood. This reliability makes them potent in shaping the timing and ease of concept acquisition. Sensorimotor cues appear less reliable in L2, as the concepts are often learned in classroom settings without direct physical or sensory engagement. Diminished reliability of sensorimotor cues reduce their explanatory power in L2 AoA. And as for availability, frequency explained more variance in AoA for L2 English than for L1 Chinese. This highlights that frequency is a more consistently available cue in L2 learning, while in L1 sensorimotor cues are more readily available.

The study with Pitjantjatjara-English bilinguals by Greenacre, Defina, Akbar, and Garcia (2024) also provides a rich framework for illustrating cue competition, cue strength, cue reliability, and cue availability in language processing, while also demonstrating how the Competition Model can be linked to mental model construction to account for linguistic relativity effects. Pitjantjatjara, an Indigenous Australian language, lacks specific comparative constructions and primarily uses conjoined comparatives (e.g., *X is tall. Y is short.*). Additionally, it has a limited range of lexicalized numerals. To test whether linguistic differences affect magnitude processing, Pitjantjatjara-English bilinguals compared quantities of dots (numerosity) and lengths of lines (extent). Accuracy and reaction times measures were taken on the tasks completed in both languages on different days. The results revealed no significant differences in numerosity comparisons across the two languages. However, in extent comparisons, participants showed lower accuracy in Pitjantjatjara, particularly as magnitudes increased and differences between items became smaller. These findings suggest that linguistic structures influence cognitive processing through cue competition. In the extent comparison task, Pitjantjatjara's conjoined comparatives offered less specific comparative cues than did the dedicated morpho-syntactic constructions in English (e.g., *taller than)*. This created competition between the linguistic strategy (conjoined comparatives) and non-linguistic strategies (e.g., estimation) for solving the task. The study found that accuracy decreased in Pitjantjatjara for more challenging comparisons, suggesting that the weaker linguistic cue (conjoined comparatives) struggled to compete effectively against other cues, resulting in less accurate judgments. In terms of cue strength, grammaticalized comparative constructions in English provided strong, explicit cues for making judgments about magnitude, enabling more accurate performance in extent comparisons. Conversely, Pitjantjatjara's implicit conjoined comparatives presented weaker cues, as they rely heavily on contextual interpretation rather than explicit linguistic marking. This difference in cue strength likely underpinned the observed disparity in task accuracy between the two languages. Regarding cue reliability, the comparative structures in English showed increased reliability for extent comparisons because they clearly outlined the domain of comparison. In contrast, Pitjantjatjara's conjoined comparatives required participants to infer the comparison domain, which introduced ambiguity and reduced reliability, especially as task complexity increased. This interpretation aligns with the finding that accuracy in Pitjantjatjara decreased as the magnitude differences narrowed. In terms of availability, English speakers are frequently exposed to and rely on dedicated comparative constructions, making these cues highly available. In contrast, Pitjantjatjara speakers use conjoined comparatives, which is a cue available in their L1, but its implicit nature may hinder its utility in precise magnitude tasks. For bilingual participants, the English comparatives likely became a more dominant cue, facilitating L2 performance. Greenacre et al. (2024) closely aligns with the Competition Model's core mechanisms, particularly cue competition, cue strength, and cue availability. This study demonstrates how grammatical structures interact with perceptual judgments in bilingual speakers, integrating embodied simulation with linguistic cue-based processing. For critical complementary insights, it can be beneficial for future research to explore how perceptual effects relate to cue dynamics in various other bilingual perceptual domains such as colour (e.g., Malik-Moraleda, Roca, & Gibson, 2022) or olfaction (e.g., Jończyk, 2016).

To sum up the collective role of the key concepts within the context of L2 acquisition, cue strength reflects the overall influence a cue exerts on processing and emerges as a function of both cue availability and cue reliability. Cue availability captures the frequency and salience of a cue in the learner's input. Cue reliability refers to the consistency of a cue with respect to linguistic functions. In relation to the development of L2 mental models, cue strength is not static but evolves over time as learners' exposure increases and embodied experiences accumulate. In formal L2 learning environments, however, cues are often encountered abstractly or symbolically. This can reduce their availability and obscure their reliability, ultimately weakening cue strength. In contrast, embodied learning activities, such as gesture-based instruction or interaction in immersive environments, can enhance both cue availability (via multisensory input) and cue reliability (by reinforcing stable mappings between linguistic forms and perceptual experiences). These enriched experiences, in turn, contribute to the formation and refinement of L2-specific mental models.

3. Entrenchment of L1 mental models

The Competition Model (MacWhinney, 2021) identifies entrenchment and transfer as two key risk factors that hinder smooth L2 learning. Entrenchment involves the strengthening of reliable cues through repeated use, making these cues highly automatic in processing. While this automaticity supports fluent L1 comprehension, it poses challenges for L2 learning, particularly when L1 and L2 cues conflict. Rather than directly "blocking" L2 development, entrenchment may bias learners toward defaulting to L1-based strategies, especially in early or effortful L2 processing.

Recent research on mental simulation in bilingual and L2 processing (e.g., Norman & Peleg, 2022; Chen, Su, & Wang, 2024; Wang & Zhao, 2024) has revealed that L1 mental models tend to exhibit stronger perceptual grounding than those formed in later-acquired languages. Entrenched L1 mental models, formed through repeated exposure and use, strengthen the reliability and automaticity of perceptual cues, which are then preferentially activated during language comprehension. For example, Norman and Peleg (2022) investigated mental simulation effects in bilingual speakers using a sentence-picture verification task in L1 Hebrew and L2 English. Participants read sentences and then verified whether images matched or mismatched the sentence's implied shape (e.g., The girl saw the lemon in the garden vs. The girl saw the lemon in the tea). Compatibility effects – faster response times for shape-matched versus shape-mismatched conditions – were observed only in L1 but not in L2. The authors attributed this asymmetry to differences in learning contexts: Hebrew was acquired through rich, embodied experiences in naturalistic settings, whereas English was learned primarily in formal instructional settings, which may not effectively foster embodied connections. The absence of simulation effects in L2 likely reflects weaker cue strength (i.e., low availability and reliability of sensorimotor cues). The strong and automatic activation of entrenched L1 patterns may reduce cognitive flexibility, making it more difficult for learners to establish new perceptual grounding in L2 unless such cues are consistently reinforced through experiential input.

One recent example of how L1 mental models exhibit entrenchment is the study of Chen et al. (2024), who examined how multilingual speakers mentally simulate concepts across their L1, L2, and third (L3) language. Using an immediate and a delayed sentence-picture verification task, two experiments explored perceptual representations both during working memory and long-term memory stages. Participants read sentences in Cantonese (L1), Mandarin (L2), and English (L3), followed by images that either corresponded or conflicted with the sentence content (e.g., a picture of an eagle with spread or folded wings paired with the sentence *There was an eagle in the sky*). Accuracy and reaction time analyses showed that perceptual representations were present in L1 comprehension but absent in L2 and L3, regardless of whether the task engaged working memory or long-term memory. The match effects found only in L1 show that native language concepts are preferentially processed through embodied, perceptual mechanisms. In contrast, L2 and L3 comprehension lacks such embodied perceptual grounding, relying instead more on symbolic representations. This centrality of L1 cues underscores how entrenched patterns shape the processing hierarchy, making L1 the primary system for grounding language in perceptual experiences. The findings from both experiments jointly suggest that repeated use of L1 during early language acquisition establishes strong and reliable perceptual cues linking linguistic forms to sensorimotor experiences. Over time, these connections are reinforced, making their recruitment automatic during L1 comprehension. The absence of match effects in L2 and L3, even for highly proficient L2 speakers, suggests weaker cue strength for sensorimotor information, largely due to reduced availability and reliability of embodied input in later language learning contexts. This suggests that entrenched L1 patterns may continue to be privileged unless L2 experiences are sufficiently rich to support the emergence of new embodied links.

Another illustration of L1 mental model entrenchment comes from Wang and Zhao (2024), who used image-schematic diagrams to explore how bilingual speakers process spatial and abstract language in their L1 and L2. The study involved 41 native Mandarin speakers, with 21 completing tasks in L1 Mandarin and 20 in L2 English using translation-equivalent sentences in spatial and abstract conditions (e.g., *Some tourists walked into the park/Some graduates stepped into society*). Participants assessed the congruence between sentences and diagrams (e.g., a congruent *into diagram* or an incongruent *out-of diagram*) displayed immediately after sentence presentation. The results revealed strong mental simulation effects during L1 processing, consistent across both spatial and abstract concepts, whereas L2 processing demonstrated weaker effects, with interference observed only for spatial concepts. Congruency or match effects observed in L1, and only traceable to a limited extent in L2, highlight how deeply entrenched L1 processing mechanisms can be. These findings point to the durability of L1 simulation routines, particularly when conceptual mappings are grounded in rich embodied experiences. The absence of robust L2 effects suggests that entrenched L1 simulation patterns may limit the salience or reliability of embodied cues in L2, making it harder for L2 to achieve comparable levels of embodied spatial representation.

From a Competition Model perspective, this suggests that spatial grounding of abstract meanings in L1 reflects high cue strength and early reliability, whereas in L2, the weaker cue strength for such mappings constrains simulation effects. In sum, the findings highlight that L1 entrenchment underscores the strength and stability of native language processing routines, and they also illustrate the challenges faced in adapting these routines for learning and processing a second language.

4. Transfer of L1 mental models in L2 processing

The Competition Model's emphasis on entrenchment and transfer aligns closely with the Revised Hierarchical Model (Kroll & Sholl, 1992; Kroll & Stewart, 1994) of bilingual memory representation. According to this model, early stages of L2 word learning are characterised by a heavy reliance on L1 words as a mediator, where L2 forms are linked to conceptual meanings parasitically and indirectly through L1 lexical connections. Early L2 comprehension and production thus rely heavily on L1-mediated pathways. As learners become more proficient, direct conceptual links between L2 words and conceptual memory gradually emerge and strengthen, enabling more independent and efficient L2 processing. The Competition Model readily extends this model of bilingual word learning to the domains of syntax (McDonald, 1989) and phonology (Flege & Bohn, 2021). The model argues that entrenchment and the need to communicate force the learner to engage in transfer of L1 form-function mappings to L2.

Although empirical evidence on the transfer of mental models in bilingual processing is limited, the few existing studies have shown both positive and negative transfer of L1 mental models. Entrenched L1 mental models can either facilitate or hinder the development of nativelike mental representations during L2 processing. For example, Nishide, Zhao, and De Deyne (under review) investigated how L1-L2 crosslinguistic (dis)similarity influences the mental representations of Dutch(L1)-English and Japanese(L1)-English bilinguals in L2 incremental sentence processing. They focused on English locative prepositions (e.g., *The teacher walked in the classroom*), which allow for dual locative (walk inside the classroom) and directional (walk into the classroom) interpretations. Dutch shares this dual interpretation, whereas Japanese only allows the locative interpretation. They used a sentence-video verification task conducted within a self-paced reading paradigm. The results confirmed a robust L1 transfer effect. Despite having advanced proficiency in English, the Japanese participants *thought in their L1* and strongly favoured the locative interpretation. Dutch learners, however, readily accepted both interpretations, similar to the English native speakers. Learner factors (L2 proficiency, onset age of L2 acquisition) only influenced the Dutch participants, whose L2-English mental model is not "overshadowed" (Ellis, 2006a) by a dissimilar L1 mental model.

Ahlberg, Bischoff, Kaup, Bryant, and Strozyk (2018) explored mental simulation involved in processing German spatial prepositions in both L1 and L2, focusing on auf (on), über (above), and unter (under). These prepositions display a spatially split usage, similar to the English distinctions between on and above. The researchers compared native German speakers with two groups of L2 learners from different L1 backgrounds: one group with a similar L1 pattern (split usage) and the other with a dissimilar L1 pattern (without split usage). Most of these learners had a >B2 level of German proficiency according to the CEFR levels. Ahlberg et al. observed an action compatibility effect and noted that the patterns of this effect differed between the dissimilar and similar L1 groups, indicating a strong influence of L1 dis/similarity.

These two studies provide convincing empirical evidence for the impact of L1 mental models on L2 word and sentence processing. This finding aligns closely with the recent simulation-based L2 comprehension model proposed in Fig. 1. The model builds on the L1 comprehension framework developed by Bergen and Chang (2008) and assumes that same as L1 comprehension, L2 comprehension also involves cognitive simulations grounded in real-world experiences. It argues that mental models are a central feature in gaining full L2 control. The cognitive procedures underlying mental simulation in L2 processing are

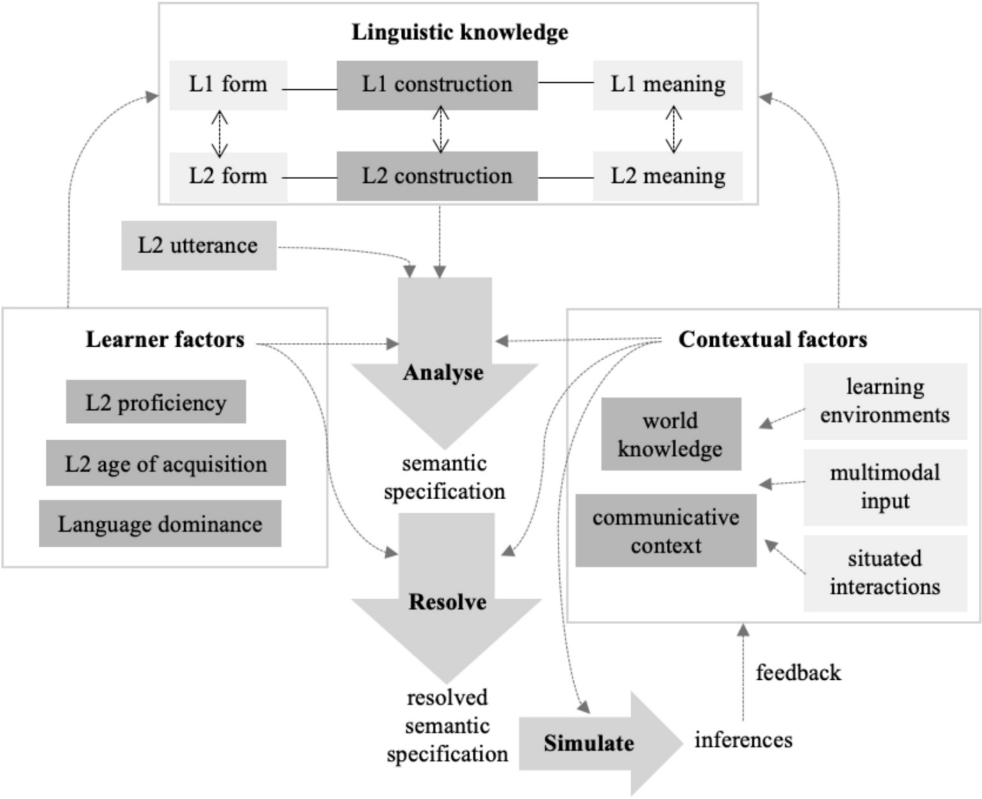

Fig. 1. Simulation-based L2 Comprehension Model (refined from Wang & Zhao, 2024).

not qualitatively different from those in L1 processing (Vukovic & Williams, 2014). Simulation-based L2 comprehension involves three interconnected processes: constructional analysis, contextual resolution, and embodied simulation. These processes mirror those in L1 models (Bergen & Chang, 2008) but are moderated by learners' linguistic knowledge of L1 and L2, learner-specific characteristics (such as proficiency and age of acquisition), and contextual factors (e.g., immersive experiences and multimodal input).

In this model, linguistic knowledge comprises learners' understanding of lexical and grammatical constructions across their languages. Each construction represents a structured association between form (e.g., phonological, orthographic, morphosyntactic features) and meaning (e.g., conceptual schemas). The model incorporates the notion that bilinguals simultaneously activate representations from both languages at the lexical, syntactic, and conceptual level (Li & Gollan, 2018; Zhao & Li, 2013). L1 and L2 constructional knowledge resides within a shared representational space. The linkage between the two language systems is illustrated by bidirectional arrows that connect L1 and L2 constructional knowledge (see Fig. 1). The explicit highlight of cross-linguistic interactions is consistent with established psycholinguistics models such as the BIA+ model, which posit interconnected bilingual lexicons and semantic systems. Furthermore, learners' linguistic knowledge is dynamically influenced by learner-specific factors and contextual conditions, which collectively modulate the activation and interplay between L1 and L2 representations throughout comprehension.

- Stage 1 (**Constructional Analysis**): At this stage, learners identify L2 constructions from input in L2 utterances. This involves associating forms with functions (comprehension) or functions with forms (production) in the L2. The process of L2 constructional analysis occurs alongside the simultaneous activation of L1 constructions (Kroll & Bialystok, 2013). As L1 is typically more dominant, transfer is inevitable. Cross-linguistic similarities facilitate positive transfer, while significant differences require greater cognitive effort to dissociate from the L1 model. The presence of corresponding L1 constructions determines the ease with which learners can form mental simulations in L2. At this stage, constructional analysis is primarily determined by learners' linguistic knowledge of both languages and secondarily influenced by learner-specific factors (e.g., L2 proficiency, onset age of L2 learning, and language dominance), with contextual factors playing a less direct role.
- Stage 2 (**Contextual Resolution**): Semantic specifications generated during constructional analysis are refined through the integration of world knowledge, discourse context, and broader communicative context. Learners construct mental models linking referents and actions via temporal, spatial, and causal relationships. Accurate interpretation of contextual meaning depends heavily on learners' existing world knowledge and their ability to utilise lexical, syntactic, and discourse cues to build coherence and track perspective. These abilities are primarily influenced by contextual factors, such as immersive interactions in the target speech community and exposure to multimodal input, though also influenced by learner-specific factors such as L2 proficiency. Learners with prolonged exposure to L2 environments and meaningful communicative interactions are better positioned to refine their sensitivity to context-specific language use. Conversely, limited exposure to the L2 environment or insufficient contextual knowledge can lead to incomplete or inaccurate interpretations.
- Stage 3 (**Embodied simulation**): This final stage involves sensorimotor activation to generate mental representations underlying action and perception aligned with L2 constructions in contextual use. The representations resulting from simulation determine subsequent processing and provide the basis for the learners' responses in language use and interaction. Importantly, the model reflects the dynamic nature of incremental processing (O'Grady, 2005) and incorporates a feedback loop that connects the stages. Errors in embodied simulation (Stage 3) would lead learners to revisit or revise constructional analysis (Stage 1). The feedback mechanism reflects the iterative nature of learning and processing in both L1 (MacWhinney, 2004) and L2 (Kowalski, Zhang, & MacWhinney, 2014).

Connecting with the Competition Model (MacWhinney, 1992, 2018) and the Revised Hierarchical Model (Kroll & Sholl, 1992; Kroll & Stewart, 1990), the Simulation-based L2 Comprehension Model posits that, in the early stages of L2 acquisition, L2 mental simulation may rely on L1-mediated imagery due to the indirect links in conceptual memory. Over time, as direct L2-conceptual connections strengthen, learners can engage in native-like mental simulation, particularly in immersive and communicative environments. The role of entrenched L1 links may not be strictly inhibitory; instead, existing conceptual scaffolding may either facilitate or constrain the formation of L2-specific simulations depending on L1-L2 similarity and the richness of L2 input.

Proficiency, learning environment, and immersion length modulate this developmental trajectory, as demonstrated by studies on L2 mental imagery, which show stronger compatibility effects in advanced learners. Compatibility effects in behavioural sentence-image verification tasks, such as those involving color (van Zuijlen, Singh, Gunawan, Pecher, & Zeelenberg, 2024), orientation and shape (Ahn & Jiang, 2018; Zeelenberg, Pecher, van der Meijden, Trott, & Bergen, 2024), and motion (Dudschig et al., 2014), demonstrate the potential for L2 learners to integrate perceptual-motor and linguistic information when sufficient semantic integration competence has been achieved. Similarly, neuroimaging evidence indicates that high-proficiency learners exhibit rapid motor cortex activation during L2 comprehension, suggesting direct access to semantic motor representations similar to native speakers (Vukovic & Shtyrov, 2014). These findings support the idea that L1 reliance in early L2 stages may not necessarily be inhibitory but rather reflect the gradual restructuring of conceptual and linguistic associations as new L2-based simulations emerge.

This Simulation-based L2 Comprehension Model requires further development in several areas. First, despite robust evidence from the existing few studies (Ahlberg et al., 2018; Nishide, Zhao and De Deyne, under review), more empirical research is needed on the impact of crosslinguistic influence on L2-based mental simulation. It is important to investigate whether L2-specific mental models can override entrenched L1-based models or whether they instead coexist as competing representational strategies. Future studies should examine whether the persistence of L1-mediated imagery reflects inhibition or simply a dependence on prior conceptual associations until sufficient L2 experience enables autonomous simulation. Second, regarding the final stage of embodied simulation, we can expand on how sensorimotor activation functions in scenarios involving culturally or contextually unfamiliar constructions. For example, idiomatic expressions or abstract language may not directly correspond to L1 experiences. Simulations for such semantically less-transparent constructions may rely more heavily on analogies or cultural schemas than on direct sensorimotor experiences. Understanding how learners generate simulations in these cases would broaden the model's applicability to diverse areas of L2 processing. Third, the model specifies how learners iterate between analysis, resolution, and simulation, dynamically adapting as they process L2 input. Few studies have examined the dynamic nature of L2 simulation (Nishide, Zhao and De Deyne, under review), particularly in the context of managing L1 interference or processing novel linguistic constructions. Future studies could explore whether learners engage in multiple cycles of refinement, where early-stage analyses may be revised based on contextual cues or sensorimotor experiences. Fourth, most existing studies focus on a narrow set of learner factors, such as L2 proficiency, while largely neglecting contextual influences. Future studies could investigate a broader range of learner and contextual factors, such as learning environments (e.g., immersive vs. classroom-based instruction), individual cognitive differences, and multimodal input (e.g., audiovisual input or embodied interactions), to better understand how these variables shape the development of L2 mental simulation.

5. Decoupling and functional restructuring

The concept of decoupling refers to reducing the dependence of a second language (L2) on the first language (L1), enabling L2 to function as a more autonomous linguistic system. This concept was proposed in a later version of the Competition Model (MacWhinney, 2018) as an important support factor that promotes successful L2 learning and fluent language functioning. Operationally, decoupling can be identified through behavioural or neural markers showing L2-specific processing that is independent of L1 activation. Complementing decoupling, functional restructuring involves adapting or reorganising cognitive and neural systems to meet the demands of processing two languages. Functional restructuring can be evidenced as shifts in neural activation patterns, including changes in the recruitment of brain areas during L2 processing relative to L1.

Importantly, decoupling is not solely an outcome observable during the moment of processing; it also represents a broader developmental process that extends over repeated instances of language use, reflection, interaction, and mental model construction. It encompasses the gradual construction and reinforcement of L2-specific mental models. It is supported by resonance – a learning principle within the Unified Competition Model (MacWhinney, 2012) that describes how repeated co-activation of L2 forms and meanings strengthens L2-specific neural connections. Through repeated exposure, inner speech, and communicative use, resonance helps consolidate associations in the learner's constructional, lexical, and phonological maps, gradually reinforcing L2-specific representations and reducing reliance on L1-mediated pathways. This cumulative strengthening supports the formation of independent L2 mental models and minimizes the risk of negative transfer. For young simultaneous bilinguals, some initial separation of mental models may naturally occur due to early exposure to both languages. However, for sequential bilinguals, achieving this separation often requires explicit engagement in L2-focused activities, such as conversational interaction and internal L2 rehearsal. These practices align with Vygotsky's concept of inner speech (Vygotsky, 1934), where learners consciously construct meaning through self-directed use of the target language without reverting to L1.

A strong collection of empirical evidence for decoupling and functional restructuring comes from behavioural and neuroimaging studies examining how L2 learners achieve nativelike simulations when processing motor-related L2 words. Behavioural studies by Wheeler and Stojanovic (2006) and Bergen et al. (2010) demonstrate that processing English action verbs (e.g., smile, punch, kick) involves modality-specific representations, as evidenced by interference effects in tasks involving matching verbs with images or synonyms. These effects, observed among immersion learners of L2 English from mixed L1 backgrounds, suggest that advanced learners activate effector-specific neurocognitive representations similar to native speakers. Dudschig, de la Vega, De Filippis, and Kaup (2014) further showed that German learners of English automatically reactivated location-specific experiential traces (e.g., upward response for sun and downward response for root) when processing L2 words. This compatibility effect indicates that L2 learners can access embodied experiential traces in L2 without relying on L1-mediated pathways.

Recent neuroimaging studies corroborate these behavioural findings with direct evidence of motor region activation during L2 processing of motor-related words. For instance, using functional MRI, De Grauwe, Willems, Rueschemeyer, Lemhöfer, and Schriefers (2014) found that both native German speakers and German-L1 advanced learners of Dutch activated motor and sensory-motor brain areas when processing motor-related verbs in a lexical decision task. This similarity to native speakers indicates successful decoupling: L2 learners were activating L2-specific neural pathways independent from L1 mediation. Using electroencephalography (EEG), Xue, Marmolejo-Ramos, and Pei (2015) demonstrated that rich sensorimotor contexts enhanced the processing of body-object interaction (BOI) words (e.g., *belt* vs. *sun*) by advanced Chinese learners of English, activating parietal and sensorimotor regions. The results indicate how sensorimotor contexts can facilitate the activation of autonomous L2 mental models.

Interestingly, studies like those by Monaco et al. (2023) and Tian et al. (2020), Tian, Chen, Heikkinen, Liu, and Parviainen (2023) suggest that motor regions may play an even greater role in L2 processing than in L1, with literal language eliciting stronger motor activation than metaphorical or abstract language (Tian et al., 2020, Tian et al., 2023). This increased motor region activation does not necessarily reflect established, stable functional restructuring identical to native speaker processing. Rather, heightened motor activation in L2 could indicate additional cognitive effort or compensatory mechanisms involved in the ongoing process of establishing autonomous L2 neural pathways. In other words, elevated activation in sensorimotor areas during L2 processing can signal both ongoing decoupling (effortful establishment of autonomy from L1) and an active process of functional restructuring (recruitment and reconfiguration of neural resources to accommodate L2-specific demands). This interpretation aligns with the broader idea that L2 learning involves dynamic neural adaptation (Stein, Winkler, Kaiser, & Dierks, 2014; Li & Jeong, 2020), where functional restructuring and decoupling are best viewed as gradual, incremental processes rather than binary outcomes. Thus, evidence in support of functional restructuring need not require exact alignment with native speaker neural patterns, but instead may be reflected by systematic shifts and increased neural recruitment as learners progressively build and solidify new, L2-specific embodied pathways.

While the above studies emphasize motor involvement in L2 processing, others extend these findings to simulations based on visual perceptual properties. Vukovic and Williams (2014) investigated interlingual homophones, which introduce cross-linguistic ambiguity (e.g., *bone* vs. *bean*), and found that highly proficient Dutch(L1)-English(L2) bilinguals automatically simulated perceptual properties like distance in L2 sentence processing, despite potential L1 interference. Similarly, Ahn and Jiang (2018) used a sentence-picture verification task to show that advanced learners of English could achieve nativelike compatibility effects with imagery-based manipulations of orientation and shape, reflecting effective decoupling and restructuring in L2 processing. Zeelenberg et al. (2024) further confirmed these effects using a delayed picture recognition task, demonstrating that highly proficient L2 learners of English could simulate implied visual shapes during L2 sentence processing, leading to enhanced recognition memory. Together, these findings reinforce the role of perceptual simulations in reducing L1 interference and promoting autonomous L2 processing.

Expanding beyond simulations of motor and visual perceptual properties, Wentura, Shi, and Degner (2024) explored the integration of sensory and abstract (amodal) representations in L2 processing and demonstrated how L2 processing can exhibit separate, functionally restructured mental models in the L2. The design used a modality-switch task with 42 German-French and 37 French-German proficient bilinguals, who evaluated noun-adjective pairs (e.g., *keys – jingling*) in both languages, determining whether the adjective accurately described the noun or not. This approach measured cognitive costs associated with switches between sensory modalities (e.g., from visual *ladder – black* to olfactory *soap – perfumed*) compared to staying within the same modality. Results showed modality-switch effects (MSE) in both L1 and L2 French, indicating that sensory-based processing occurs in L2 too. Absence of MSE in German L2 suggests that German-French bilinguals processed German L2 differently from French L2, not transferring embodied representations from L1. Stronger MSEs in French suggests that L2 use can help establish and reinforce L2-specific neural pathways, reducing the risk of negative transfer from L1 by creating decoupled, independent mental models for L2. For German, weaker reinforcement of sensorimotor pathways in L2 processing may indicate limited activation of modality-specific features, which could inhibit the formation of autonomous neural pathways. Unlike for L2 French, the lack of significant MSE in L2 German suggests incomplete decoupling or restructuring, where embodied mechanisms or sensorimotor activations may not be fully engaged for L2 processing. These results highlight the variability in decoupling outcomes, influenced by language-specific factors and levels of sensorimotor engagement in L2 processing.

Another study to provide insights into decoupling and functional restructuring in bilingual language processing (Vanek et al., 2024) examined the processing of negation in L1 and L2 by monitoring eye movements on a blank screen during sentence comprehension. The study involved 32 native Croatian speakers and 32 Croatian learners of English, who listened to sentences containing different forms of negation and affirmation in both languages. Eye tracking was used to capture anticipatory gazes toward expected visual information in the absence of actual images to reflect mental simulations. The study found that Croatian learners of L2 English launched anticipatory eye movements when processing negation, reflecting predictive mechanisms independent of L1 structures. Despite structural differences between Croatian (negative concord) and English (negative quantifiers), learners processed L2-specific negation types effectively, showcasing their ability to adapt to L2 structures without overreliance on L1 templates. Participants did not exhibit significant difficulties or errors when processing L2 negation, even though Croatian negative concord involves multiple cues while English negation via negative quantifiers relies on a single cue. Despite the complexity and potential for confusion due to differing negation structures in L1 and L2, the learners' successful processing of both negative concord and negative quantifiers demonstrates their ability to establish distinct mental models for each language. An absence of L1 interference supports the notions of decoupling and functional restructuring as learners effectively managed L1-L2 structural differences, evidenced as reliance on L2 structures to guide their L2 processing.

6. Conclusion and future directions

This article revisited the foundational principles of the Competition Model considering recent advances in mental simulation research, highlighting how embodied cognition provides a richer understanding of bilingual processing. By exploring the dynamics of cue competition, transfer, decoupling, and functional restructuring, it underscored the intricate mechanisms of linguistic, cognitive, and sensorimotor processes in bilingualism. Notably, the findings of the surveyed studies suggest that entrenched L1 mental models dominate early L2 processing but can be progressively restructured to achieve more autonomous and nativelike L2 functioning through processes of decoupling and embodied simulation. While empirical studies have demonstrated that advanced learners can achieve nativelike perceptual and motor simulations in L2 processing, considerable variability remains, due to factors such as crosslinguistic similarity, proficiency, learning context, and immersion. Notably, individual differences in cue weighting, i.e., how learners attend to prioritise linguistic, contextual, or perceptual cues, may affect simulation outcomes. Some learners are more attuned to perceptual detail or better at managing cognitive load, which would affect their ability to process and integrate low-salience or competing cues (Ellis, 2006b). Learners with greater working memory, attentional control, or perceptual sensitivity may more readily detect, retain, and integrate cues in real-time processing (Kidd, Donnelly, & Christiansen, 2018). Such findings highlight the need for future research to examine how cognitive and experiential factors, such as language exposure, learning history, and executive control, mediate individual trajectories in the development of L2 mental simulation.

These findings also point to the importance of linking work on mental model construction to other aspects of the Competition Model, including the theories of transfer, decoupling, and emergent linguistic levels (MacWhinney, 2015). The Perspective Hypothesis (MacWhinney, 1977, 2008) describes sentence processing as the dynamic construction of an embodied mental model based on the act of taking the perspective of the subject of a clause, as well as grounding the model in terms of spatial, temporal, and deictic relations. Within the fuller theory of emergent structural levels, we can view the details of L2 mental model construction as being shaped by expectations from both the lexical level (Nishide, Zhao and De Deyne, under review) and the level of syntactic constructions (Vanek et al., 2024). Together, these effects provide evidence for a certain type of processing linguistic relativity that effects not only "thinking for speaking" (Slobin, 1996) but also "thinking for listening".

Existing research findings showing successful functional restructuring predominantly rely on samples of highly proficient bilinguals from Indo-European language backgrounds, which often feature relatively close linguistic distances. Further studies with more diverse language representations are needed to explore how L2-specific mental models can override entrenched L1 models, particularly in cases of significant linguistic dissimilarity. Advanced neuroimaging methods, such as real-time fMRI and EEG, along with data analysis methods like functional and structural connectivity analysis (Bastos & Schoffelen, 2016) can be employed to investigate the neural pathways involved in functional restructuring. These methods could reveal the distinct connectivity patterns between target languages, sensory-motor regions, and semantic areas during L1 and L2 processing (Monaco et al., 2023).

As concrete practical implications of these theoretical insights for second language learning, cue manipulation tasks simulating real-world environments can be integrated into instructional designs to strengthen learners' sensitivity to reliable L2 cues, for instance to train extent comparison accuracy (Greenacre et al., 2024) via visual aids co-presented with morphosyntactic cues alongside conjoined comparatives. Embodied learning activities, such as Total Physical Response (Asher, 1969) and gestures (Morett et al., 2012), role play in simulated scenarios, and the use of image-schematic diagrams (Zhao, Huang, Zhou, & Wang, 2020) can be used to enhance perceptual grounding and accelerate the functional restructuring of L2 mental models. Immersion environments and interactive tools (e.g., VR virtual reality P. Li & Jeong, 2020) that stimulate sensorimotor systems can be employed to promote decoupling from L1 and trace how trajectories of autonomous L2 processing, for instance in L2 negation (Vanek et al., 2024), develop.

In particular, high-immersion VR environments offer 360° visual input and allow learners to interact with richly contextualised, first-person environments via avatars. These avatar-based interactions stimulate learners' motor and perceptual systems and enables them to move, gesture, and engage with virtual objects, while grounding linguistic meaning in bodily experience (Taguchi & Hanks, 2024). This sensory-rich immersion fosters a heightened sense of presence, comprising physical, social, and self-presence, which enables learners to feel "situated" within a scenario (Makransky et al., 2017; Slater, 2018). Learners in VR have reported significantly higher levels of body ownership, agency, and embodied learning compared to those using desktop-based environments (Klingenberg et al., 2024). VR's affordance of anonymity through avatars lowers learners' anxiety and enhances confidence. This affective benefit promotes willingness to communicate (Kim, Zhao, & Diskin-Holdaway, 2022), a necessary condition for engaging in embodied, interactive language use (Thrasher, 2022). By simulating real-world perceptual and motor experiences, VR strengthens the availability and reliability of embodied cues in L2 comprehension and production, thus supporting the development of grounded L2 mental models. By extending beyond traditional input types, such approaches may facilitate decoupling and restructuring even in learners with limited naturalistic exposure.

The updated Competition Model links neural, cognitive, and linguistic mechanisms under a unified framework of bilingual development and processing (MacWhinney, 2012). When viewed through the lens of embodied cognition and mental simulation, it resonates with theories in construction grammar, cognitive semantics, and usage-based models of language. The new directions in this article highlight that lexical semantics and morphosyntactic constructions can be seen as emergent from and constrained by the same sensorimotor experiences that drive mental simulation. Furthermore, drawing on MacWhinney's Perspective Hypothesis (1977, 2008), these directions are taken to argue that embodied mental modeling can be integrated with discourse-level phenomena like reference resolution, deixis, and event construal, offering a pathway for exciting new research in sentence-level processing as well as discourse pragmatics in bilingual contexts. Also, future work could explore typological variation in embodiment effects, potentially aligning the Competition Model with the study of linguistic relativity and crosslinguistic influence.

Regarding interdisciplinary benefits to the Competition Model, neuroimaging findings (e.g., De Grauwe et al., 2014; Monaco et al., 2023; Tian et al., 2023) reveal that advanced L2 learners activate motor and sensorimotor brain regions, showing that L2 processing can become decoupled and restructured since it is neurally distinct from L1 processing. These findings bridge cognitive neuroscience and applied linguistics, grounding the Competition Model's abstract constructs in observable neural activity and reinforcing the model's relevance in a range of learning scenarios. Based on this evidence, testable hypotheses for future interdisciplinary work could include, for example, longitudinal neuroimaging studies to observe the emergence of L2-specific pathways over time, or intervention studies that use embodied methods to induce structural changes in L2 learners' neural processing. Such expansions can reinforce how the Competition Model benefits from interdisciplinary approaches and pave the way for new empirically grounded research designs at the intersection of linguistics, psychology, and neuroscience.

CRediT authorship contribution statement

Helen Zhao: Writing – review & editing, Writing – original draft, Conceptualization. **Norbert Vanek:** Writing – review & editing, Writing – original draft, Conceptualization. **Brian MacWhinney:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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