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Linguistic synesthesia and embodiment: A study based on Mandarin modality exclusivity norms

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ABSTRACT

This study aims to resolve the ongoing debate about sensory modality embodiment found in linguistic synesthesia by proposing an empirical model: Perceived Strength of Embodiment (PSE). The perceived strength of embodiment for sensory adjectives is measured based on the sensory ratings of the adjectives in the five sensory modalities, while the perceived strength of embodiment for each sensory modality is calculated based on the PSE of all adjectives according to their dominant modalities. PSE is designed to address a salient dilemma in the widely-accepted modality-based embodiment asymmetry: that is, such asymmetry fails to predict the directionality behaviors between sensory words because each sensory word is typically associated with more than one modality, and each may have different strengths of association. Based on an analysis of sensory adjectives, we find that a lexical concept-based embodiment asymmetry better explains the data than a modality-based embodiment asymmetry and, additionally, the lexical concept-based account is supported by Mandarin synesthetic compound adjective data. In sum, this paper argues that the PSE model is an empirical approach to measuring the degree of embodiment which furthers the understanding of the role of embodiment in the linguistic conceptualization of sensory perceptions.

1. Introduction

Linguistic synesthesia is a type of language usage in which lexical items commonly regarded to be in one sensory modality are employed to describe perceptions in a different modality, such as *sweet voice* in English, 冷香 *leng3 xiang1* 'cold fragrance' in Mandarin, and *keskin bir turuncu* 'sharp orange' in Turkish (Ullmann 1957; Williams 1976; Zhao et al., 2019a; Kumcu 2021). Extensive research has found that linguistic synesthesia conforms to certain directional patterns of mappings between sensory modalities (e.g., generally mapping from touch and taste to vision and hearing) (Yu 2003; Strik Lievers 2015; Jo 2019; Zhao et al., 2019a; Kumcu 2021; among others). For example, linguistic synesthesia in Mandarin Chinese was demonstrated to show a hierarchical model of mapping directionality by Zhao et al. (2019a), as shown in Fig. 1. To explain the directional

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preferences observed in linguistic synesthesia, various studies have proposed that there are embodiment asymmetries of sensory modalities that motivate synesthetic mappings from more embodied modalities (e.g., touch and taste) to less embodied ones (e.g., vision and hearing) (Shen 1997; Yu 2003; Popova 2005; Shen and Eisenman 2008; Shen and Gadir 2009)[1].

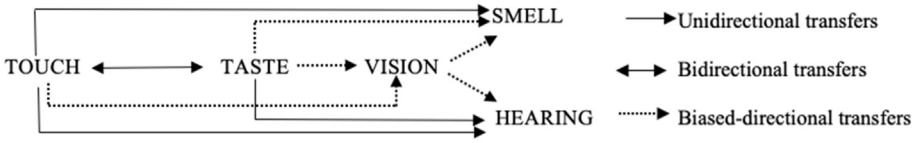

Fig. 1. Directionality of linguistic synesthesia in Mandarin Chinese (Zhao et al., 2019a: 9).

This study aims to test the hypothesis of sensory modality embodiment asymmetries in linguistic synesthesia based on Mandarin modality exclusivity norms. Specifically, an experiment of sensory rating tasks on Mandarin synesthetic adjectives (i.e., adjectives with synesthetic usages) is conducted to test whether sensory modalities show different degrees of embodiment in linguistic synesthesia.

In what follows, Section 2 reviews the notion of embodiment with a focus on the degree of embodiment, the hypothesis of sensory modality embodiment asymmetries, and the modality exclusivity norms. Section 3 proposes an empirical model to measure embodiment based on the Perceived Strength of Embodiment (PSE). Section 4 elaborates on data collection of sensory ratings of Mandarin synesthetic adjectives. Following that, Section 5 and Section 6 present the results and discussion, respectively. The last section summarizes the findings of this study and suggests directions for future research.

2. Embodiment and modality exclusivity norms

2.1. Embodiment and degrees of embodiment

Embodiment is theoretically grounded on embodied cognition, whose tenet is that human cognitive processes are situated and defined by bodily interaction with the world (Wilson 2002; Shapiro and Spaulding 2021; Torres-Martínez 2022). Depending on the representation of cognitive content, the theories of embodied cognition can range from the radical (i.e. strong) view to the so-called "disembodied" view (i.e., weak) (Meteyard et al., 2012). The radical theories claim that all cognition can be reduced to sensory and motor information. The "disembodied" theories, on the other hand, model cognitive contents as conceptualized abstract representations[2]. The nature of representation has been one of the central issues in the study of embodied cognition (Mahon and Caramazza 2008; Körner et al., 2023). It will also play a central role in motivating our current proposal. In what follows, we use the more neutral terms of strong vs. weak to refer to these two types of theories both for clarity and to avoid unintentional implications.

Empirical evidence to support embodied cognition was presented from two different sources in previous studies. The first is to show that human physical systems, such as sensory and motor systems, are involved in cognition. For instance, Lakoff (2008, 2014) assumed that the semantic content was represented by the simulation of sensory and motor content in a distributed network. Such evidence can be obtained from experiments, especially those that manipulate the embodied activities to test their effects on cognition. Tversky and Hard (2009), for instance, manipulated the physical location and interaction to show their effects on spatial cognition. The second approach is to show that embodiment plays a systemic role in the cognitive system. That is, if the human cognitive system, inclusive of all sensorimotor systems, is grounded on embodiment, then the concept of embodiment could play a role in predicting how these cognitive sub-systems interact. In this context, the concept of the degree of embodiment is often invoked but has yet to be precisely defined. Generally speaking, it is assumed that the concepts involving higher degrees of embodiment are cognitively more accessible. One classical case is the Conceptual Theory of Metaphor (Lakoff and Johnson 1980), in which metaphor is defined as an abstract (i.e., less embodied) object being expressed by a concrete (i.e., more embodied) object. So far, studies taking this approach are typically based on intuitive assignments of degrees of embodiment.

State-of-the-art surveys of the theoretical and experimental studies of embodied cognition in the past 15 years have reached very similar conclusions. Mahon and Caramazza (2008), Meteyard et al. (2012), and Mahon (2015) have concluded

[1] Please note that there is no agreed-upon model for delineation and classification of sensory modalities (see Miller and Johnson-Laird 1976; Purves et al., 2001[2000]; Cacciari, 2008). However, as noted by Winter (2019), the five Aristotelian senses (i.e., touch, taste, vision, hearing, and smell) as a cultural framework, which is well recognized by the speakers of a particular language (e.g., English and Mandarin), could provide a suitable standpoint for the examination of the relationship between language and perception. This study, following previous research on linguistic synesthesia (e.g., Shen 1997; Strik Lievers 2015; Zhao et al., 2018; Kumcu 2021), adopts the classical model of the five sense modalities.

[2] A reviewer, against the "disembodied" cognition, pointed out that the concept of representation is not precise enough to describe how human brains respond to stimuli, following Favela and Machery (2023). Note that Favela and Machery (2023) have also found that there are few variations in the application of the concept of representation to describe brain activities when responding to specific stimuli.

that neither the strong embodied cognition theories nor the weak theories are supported by the reported study results. In other words, an optimal theory of embodied cognition likely has to take into account certain degrees of interaction between the sensorimotor experience and the abstract representation of the cognitive content. Körner et al. (2023), the most recent and comprehensive survey covering the data from six different linguistic levels, concluded similarly and called for both more interactive integrated theories as well as more powerful tools. Following these surveys, this study adopts a view that can be broadly defined as grounded interaction (Mahon and Caramazza 2008), instead of either the strong or weak views, and aims to provide a new tool[3].

2.2. The hypothesis of embodiment asymmetries of sensory modalities

Given the heterogeneity of the views and theories of embodied cognition, neuro-cognitive scientists considered it unlikely that a single homogeneous gradable scale would be able to evaluate degrees of embodiment (see Wilson 2002; Chemero 2011; Meteyard et al., 2012; Wilson and Golonka 2013). In contrast, cognitive linguists generally assumed that human experiences and the corresponding concepts could be differentiated with different degrees of embodiment, based on whether bodily contact and interactions with the surrounding environment are involved (Lakoff and Johnson 1980; Johnson 1987; Gibbs 2005; among others).

In order to explain the synesthetic mapping directions, sensory modalities have also been hypothesized to show embodiment asymmetries, which motivate synesthetic mappings from more embodied modalities (e.g., touch and taste) to less embodied ones (e.g., vision and hearing). Specifically, Shen and Eisenman (2008: 111–113) have argued that in terms of the bodily contact involved in the cognitive process, touch and taste are "direct," as these two modalities require immediate contact between sensory organs and perceived objects. Shen (2008: 302) has assumed that touch, taste, and smell are phenomenologically experienced as physiological sensations of experiencers, while vision and hearing are more "object-based sensations," which are experienced attributed to the perceived objects external to human bodies. In terms of the shared experience of the whole body, the sensory organ for the tactile sensation is distributed all over the body, while the other four modalities have specialized sensory organs (Shen 1997). Thus, Shen and colleagues have claimed that touch is the most embodied, followed by taste and smell; vision and hearing are the least embodied (Shen 1997; Shen and Cohen 1998; Shen and Eisenman 2008; Shen and Gadir 2009). Yu (2003) and Popova (2005) suggested a similar proposal that sensory modalities showed asymmetries of embodiment in linguistic synesthesia based on different perceptual asymmetries.

On the other hand, the hypothesis of embodiment asymmetries of sensory modalities has been challenged. Rakova (2003) argued that sensory modalities were difficult to distinguish in terms of experiential primacy, as they were all embodied. Winter (2019) pointed out that the perceptual asymmetries, the main empirical motivations for the proposed embodiment asymmetries, could change with different perceptual tasks or qualities. For example, Shibuya et al. (2007: 217) suggested a sight-to-touch asymmetry, based on the fact that "the tactile sense often involves the use of the visual sense," where vision thus dominates touch in perception. However, Ronga et al. (2012) observed that visual information could be simultaneously obtained when touching something, while tactile information could not be generally obtained when seeing an object. Hence, the tactile sense could be considered more dominant based on Ronga et al. (2012).

To summarize, the embodiment asymmetry and the degree of embodiment are two basic and correlated concepts in the proposal of embodiment asymmetries of sensory modalities, where sensory modalities are hypothesized to have varying degrees of embodiment due to involving different faculties of the body and processing different observable physical properties. In addition, given that a specific favored mapping direction (i.e., an asymmetry in mapping directionality) between two sensory modalities has been observed in the lexical conceptualization of linguistic synesthesia (e.g., Strik Lievers 2015; Jo 2019; Zhao et al., 2019a; Kumcu 2021; Zhao et al., 2024), the proposal of embodiment asymmetries of sensory modalities further hypothesizes that the asymmetric relation in linguistic conceptualization between sensory modalities reflects and can be predicted by the different embodiment degrees of sensory modalities. However, the experimental studies by Werning et al. (2006) and Fishman (2022) serve as good examples to illustrate why evidence of the asymmetry in mapping directions between just two modalities does not provide sufficient support for the embodiment asymmetry of sensory modalities. Specifically, Werning et al. (2006) demonstrated that the linguistic synesthetic expressions in German with the mapping from touch to taste showed significantly higher accessibility given by participants as compared with the expressions that had a reverse direction, while the expressions with the mapping from touch to sound did not. The results contradict the prediction of the proposal of embodiment asymmetries of sensory modalities in two important ways. First, it has been generally argued that touch is the most embodied and sound the least, while taste lies in between. Thus, the degree of embodiment of touch being higher than taste and sound would predict an asymmetric relation from both touch to taste and touch to sound. However, as only the expressions with the mapping direction from touch to taste were judged to be more accessible, only the mapping asymmetry from touch to taste (but not touch to sound) was supported by Werning et al. (2006). The second, and perhaps more crucial, contradiction to the prediction of the embodiment asymmetry proposal is that the theory would

[3] Note that one challenge to the theory of embodied cognition is that there may not be modality-specific representations of word meanings in the brain, as argued by Casasanto and Gijssels (2015) and Calzavarini (2023). However, extensive research has demonstrated that modality-specificity is not a necessary condition for embodied cognition (Borghi et al., 2023; Dove 2023; Kiefer et al., 2023; Reilly and Peelle 2023). Thus, this study follows the well-recognized assumption that sensory and motor information plays an indispensable role in semantic representation and processing (Meteyard et al., 2012).

predict that the mapping between touch and sound should be more accessible than that between touch and taste, as the degree of embodiment of taste was supposed to be lower than touch but higher than sound. Similarly, Fishman (2022) found that there were only parochial asymmetries based on individual pairs of sensory modalities and that sensory modalities could not be ordered hierarchically when lexical factors were controlled for. Thus, a crucial and more interesting issue is whether there is an inherent hierarchy among all sensory modalities according to their degrees of embodiment. In other words, are the relations between all pairs of degrees of embodiments both asymmetric and transitive for the five sensory modalities? This is the embodiment asymmetry that we will be focusing on in this paper.

It is also notable that the hypothesis of embodiment asymmetries of sensory modalities presents a chicken-and-egg dilemma based on the different approaches to the representation of cognition in terms of how to measure embodiment. On one hand, the strong theories of embodied cognition argue that cognitive content can only be precisely represented by embodied experiences. This means that degrees of embodiment must be based on the measurement of embodied experiences. On the other hand, the weak theories of embodied cognition argue that cognitive content by nature involves conventionalization that can be tested at a higher and more abstract level. This means that degrees of embodiment could also be conceptually and conventionally anchored. Without conclusive evidence for either theory, how can one identify the best measurement of degrees of embodiment? In this paper, we propose a solution to this dilemma based on facts established by the modality exclusivity norms of multiple languages (e.g., Lynott and Connell 2009; Chen et al., 2019; Lynott et al., 2020; Speed and Brysbaert 2021; Zhong et al., 2022). That is, a word sense is not typically associated specifically and exclusively with a sensory modality. That is to say, the vast majority of sensory words are multi-modal in the sense that they are associated with more than one sensory modality with varying strength. This also means that the previous studies of embodiment asymmetry may fail to generate reliable results because they made the naïve assumption that each word is associated with a specific sensory modality, hence modeling the degrees of embodiment inappropriately. Central to our solution is the non-exclusive and multi-modal information provided by the modality exclusivity norms as the empirical data for the grounded interaction of embodied cognition.

2.3. Modality exclusivity norms

The modality exclusivity norms are language-specific lexical properties representing the correlation between conceptualized lexical meanings and sensory modalities[4]. Lynott and Connell (2009) initiated the sensory rating task, asking participants to rate the extent to which the meaning of a lexical item is based on sensory perceptions by touching, tasting, seeing, hearing, and smelling. Two pieces of sensory information for lexical items were obtained through the task, including (1) the degree to which each property denoted by a lexical item is associated with the five senses; and (2) the degree to which each property denoted by a lexical item belongs exclusively to one sense modality. For example, with a 0 to 5 rating scale, the English word *fresh* was given a mean rating score of 2.43 in touch, 4.10 in taste, 3.95 in vision, 1 in hearing, and 4.52 in smell. The modality exclusivity score, ranging from 0 to 1, is calculated as the range of rating values divided by the sum of the ratings, and thus the word *fresh* has a score of 0.22 (22 %) (Lynott and Connell 2009: 562). The interpretation of the modality exclusivity can be illustrated by two extreme scenarios. First, when a word is rated with a non-zero number y for one modality, but 0 for all other four modalities, its exclusivity is (y/y = 1) (100 %), since (y-0) is y, and the sum of (y+0 + 0+0 + 0) is also y. That is, the lexical concept is 100 % exclusive, as all the sensory information is derived from that particular modality. On the other hand, if a word receives the rating of x in all five modalities, its exclusivity is (0/5x = 0) (0 %), since (x-x) is 0. That is, the lexical concept is non-exclusive, as it is evenly shared by all the five modalities.

The modality exclusivity norms for English were compiled first (Lynott and Connell 2009, 2013). Lynott et al. (2020) added information related to body parts as action effectors (i.e., mouth/throat, hand/arm, foot/leg, head excluding mouth/throat, and torso) as well as the modality of interoception to the expanded norms, which is called the sensorimotor norms. To date, the modality exclusivity or sensorimotor norms have been compiled for the following languages in addition to English: Dutch (Speed and Majid 2017; Speed and Brysbaert 2021), French (Chedid et al., 2019; Miceli et al., 2021), German (Müller et al., 2022), Italian (Morucci et al., 2019; Vergallito et al., 2020), Mandarin Chinese (Chen et al., 2019; Zhong et al., 2022), and Russian (Miklashevsky 2018). The modality exclusivity and sensorimotor norms are empirical data that have been demonstrated with great utility in research on linguistic synesthesia and metaphor. For example, Zhao et al. (2022) utilized the perceptual strength of sensory adjectives collected by Chen et al. (2019) to show that there is a basic meaning for most Mandarin synesthetic adjectives. Winter and Strik Lievers (2023) operationalized the metaphoricity of linguistic expressions by using the modality exclusivity norms of English adjectives and nouns (Lynott and Connell 2009, 2013). They found that the semantic distance, which was measured by using the sensory ratings of lexical concepts, could predict metaphoricity and creativity judgments in synesthetic metaphors. Sensorimotor norms are also shown to be useful tools for modeling in natural language processing. Wan et al. (2023) and Li et al. (2024) applied the norms in detecting metaphors. Zhao et al. (2025) applied them for the emotion analysis. Additionally, Chersoni et al. (2020) showed that modality exclusivity norms could be modeled with distributional semantic data. All those studies demonstrate the range and variety of the roles modality exclusivity norms play in cognitive processes.

[4] For the clarity of the discussion, the term “modality” is used when talking about human senses and the term “domain” when talking about conceptual domains within the Conceptual Metaphor Theory (e.g., Lakoff and Johnson 1980; Gibbs 2005) in general.

Last but not least, the modality exclusivity norms do not presuppose a particular theory and cannot be interpreted in terms of either the strong or weak theory of embodiment. Thus, the modality exclusivity norms provide empirical data for exploring embodied cognition without an*a priori* commitment to a theory.

3. Perceived strength of embodiment (PSE)

In this section, we make our proposal for the measurement of degrees of embodiment based on the modality exclusivity norms, which has the advantage of being both empirical and theory-neutral. A critical literature review reveals that the previous reports of embodiment asymmetries of sensory modalities relied on subjective judgments and assignments of degrees of embodiment. A typical claim is that modality A is more embodied than modality B, and that hence they behave differently. However, the purported evidence of higher or lower degrees of embodiment cannot be independently verified. Furthermore, the tenet of embodied cognition is that cognition is grounded on sensory experiences. Treating having sensory input as the sufficient condition of embodied cognition, Rakova (2003), Winter (2019), and Fishman (2022) argue that the attempts to distinguish degrees of embodiment for sensory modalities are misleading and ill-conceived.

Given the lack of theoretical consensus on the nature of the representation of embodied cognition, as well as the objection raised to the assumption of differences in degrees of embodiment among sensory modalities, we agree that currently there is no viable empirical approach to degrees of embodiment as traditionally envisioned. On the other hand, observations of asymmetries among sensory modalities have been amply documented. For instance, sensory modalities do behave differently in linguistic synesthesia, wherein touch and taste generally act as the source domain while hearing and smell act as the target domain (see Fig. 1). In addition, we also have the attested empirical data of modality-specific conceptual strength based on the modality exclusivity norms. Note that the modality exclusivity norms collect the perceptual strength (i.e., the degree to which each sensory modality is involved) and dominance (i.e., the degree to which one sensory modality is involved exclusively) of sensory modalities in the conceptualization of the sensory lexicon. These two facts suggest that there are perceived degrees of strength at work, regardless of the actual content of embodied cognition. In other words, with neither the theory nor the tool to directly measure embodied content of cognition, we hypothesize that the attested asymmetries and variations reflect the perceived strength of these cognitive content. Thus, this study proposes the Perceived Strength of Embodiment (PSE) as an empirical and quantifiable measurement of embodiment based on modality exclusivity norms. Specifically, as the data of sensory ratings and modality exclusivity scores provides the perceptual strength and dominance of perception for each sensory modality respectively, the data can be employed to measure the perceived strength of embodiment of the perception in a given sensory modality during linguistic conceptualization. In addition, we can then aggregate these perceived strengths of perceptions in linguistic conceptualization from all modalities to estimate the perceived strength of embodiment for each sensory modality[5].

3.1. The perceived strength of embodiment of lexical concepts

Sensory ratings in the modality exclusivity norms differ from the two frequently utilized ratings of concreteness and imageability for embodiment measurement (e.g. Balota et al., 2004; Yap and Balota 2009; Brysbaert et al., 2014, 2018). Connell and Lynott (2012), Lynott et al. (2020), and Zhong et al. (2022) found that sensory ratings outperformed both concreteness ratings and imageability ratings in word processing tasks. Specifically, the concepts receiving higher perceptual ratings in modality exclusivity norms (i.e., *music*) were found to be processed faster than those receiving lower perceptual ratings (i.e., *republic*) in the tasks of lexical decision and naming (Connell and Lynott 2012; Lynott et al., 2020; Zhong et al., 2022). In addition, Connell and Lynott (2012: 460) have observed that the "textbook concreteness effects in word processing are actually a function of the degree of perceptual information in each referent concept's representation." As "concreteness" and "embodiment" have similar connotations in cognitive studies (e.g., Lakoff and Johnson 1980; Johnson 1987; Gibbs 2005), those studies have also offered support for the assumption that the perceptual strength measured by the sensory rating in the previous studies such as Lynott and Connell (2009), Chen et al. (2019), and Lynott et al. (2020) etc. would be positively correlated with the perceived strength of embodiment proposed by this study. That is, a higher perceptual strength rating might indicate a higher perceived strength of embodiment. Note that lexicalized sensory concepts are often associated with more than one sensory modality and receive different ratings in different sensory modalities (Lynott and Connell 2009; Chen et al., 2019). For example, the word *sweet* was given high ratings in both taste and smell, with mean scores of 4.86 and 3.90, respectively (Lynott and Connell 2009)[6]. This suggests that the ratings in all five senses should be considered for the general PSE of a lexical concept. In addition, this also indicates that if a lexical concept receives higher sensory ratings in more of the five sensory modalities, the experience conceptualized by the concept would be perceived to be more embodied. This is

[5] The theory of affordance suggested by Gibson (1969, 1977) was pointed out by a reviewer. The mental representations of perceived entities/events in this theory involve bundles of affordance and activate the integration of modal contents. Similar to the theory of affordance, this study does not assign sensory concepts into single-modal or multi-modal categories. The proposed Perceived Strength of Embodiment (PSE) takes a specific experience as an integration of all sensory modalities, based on the perceptual strength and dominance of the involved perceptions in linguistic conceptualization, which will be detailed in Section 3.1 and Section 3.2.

[6] This study follows the reasonable and viable categorization of the perceptual strength on a 0–5 rating scale suggested by Lynott and Connell (2009), which includes the weak (0–1.5), moderate (1.5–3.5), and strong (3.5–5) groups.

because higher ratings correspond to higher perceptual strength, and the aggregated higher perceptual strength could suggest a higher general PSE of a lexical concept. Thus, along the rating scale of 0–5, a lexical concept receiving 5 in all the five senses is the most embodied, while a lexical concept receiving 0 in all the five senses is the least embodied.

However, it is important to note that the PSE cannot be measured by relying on the perceptual strength exclusively and be calculated by the sum of the rating scores in the five sense modalities. This is because the calculation might ignore the integration of sensory modalities in a specific experience (see **Footnote** [5]). Thus, this study also takes into consideration the perceptual dominance reflected by the modality exclusivity score in the modality exclusivity norms for the general PSE of a lexical concept. The formula for measuring the PSE of lexical concepts is proposed as follows.

$$\text{PSE of lexical concept x} = \text{Mx} + \text{Mx (1-Ex)}, \tag{1}$$

where PSE = perceived strength of embodiment, Mx = the maximal (i.e., highest) rating score received among all five sensory modalities, and Ex = modality exclusivity.

The rationale for formula (1) is that the highest rating among all five modalities (i.e., Mx) sets a ceiling for the possible ratings of the PSE. In addition, the contribution of the ratings in other modalities to the general PSE is calculated as Mx multiplied by (1-Ex). Recall that Ex is the modality exclusivity (ranging from 0 to 1), and therefore (1-Ex) is the "inclusivity" (i.e., the degree of similarity between the highest rating and the ratings in other modalities). Given Mx as the maximal PSE of all the modalities for a lexical concept, Mx (1-Ex) estimates the contribution of other modalities to the general perceived strength of embodiment for the lexical concept. In addition, a lexical concept receiving a lower exclusivity score means that the ratings in other modalities are more like the maximal rating, and therefore the lexical concept would be more embodied. Thus, the PSE score ranges from 0 (i.e., for lexical concepts receiving 0 in all five senses, thus Mx = 0, and (1-Ex) = 0) to 10 (i.e., for lexical concepts receiving 5 in all five senses, thus Mx = 5 and (1-Ex) = 1), based on the sensory ratings ranging from 0 to 5.

Abstract concepts have been established to be less embodied than concrete concepts by both the theoretical studies of cognitive linguistics (e.g., Lakoff and Johnson 1980; Johnson 1987; Gibbs 2005) and the experimental research of psycholinguistics (e.g. Balota et al., 2004; Yap and Balota 2009; Brysbaert et al., 2014). This can be seen using the abstract adjective *unphysical* and the concrete adjective *beautiful* as an example. Following the proposed formula (1) for the general PSE of lexical concepts, the modality exclusivity norms can be used (e.g. Lynott and Connell 2009; Lynott et al., 2020) to calculate the PSE score for each lexical concept. The PSE score of the word *unphysical* is 3.49 out of 10, as the word has the highest rating of 2.21 in vision (Mx = 2.21) and the modality exclusivity score of 0.42, hence with (Mx (1-Ex) = 2.21 * (1–0.42) = 1.28). By contrast, the word *beautiful* has a much higher PSE score of 8.69 out of 10 based on formula (1), as it received the highest rating of 4.62 in vision (Mx = 4.62), with the modality exclusivity score of 0.12 and hence with (Mx (1-Ex) = 4.62 * (1–0.12) = 4.07). The contrast between the PSE scores of the abstract word *unphysical* and the concrete word *beautiful* illustrates the feasibility of the proposed formula for measuring embodiment for lexical concepts.

3.2. The perceived strength of embodiment of sensory modalities: PSE-S

Based on the modality exclusivity measurement (Lynott and Connell 2009, 2013), lexical concepts may be classified and assigned to a dominant modality based on the modality with the highest rating score. For instance, the dominant modality of the adjective *bright* is vision, as the visual rating of the adjective is 5, over the tactile rating of 0.19, the auditory rating of 0.14, the olfactory rating of 0.10, and the gustatory rating of 0.05 (Lynott and Connell 2009). Winter (2019) additionally suggested that the modality exclusivity of each sensory modality could be calculated based on the modality exclusivity of all words sharing the same dominant sensory modality. Combining concepts from these studies, this study proposes to aggregate the PSE of all lexical concepts with the same dominant sensory modality to establish the perceived strength of embodiment for that particular sensory modality. The Perceived Strength of Embodiment of sensory modalities (PSE-S) will, in turn, provide empirical data to test the hypothesis of embodiment asymmetries of sensory modalities. In addition, given that most of the sensory words do not exclusively belong to their dominant modalities (e.g., Chen et al., 2019), the contribution of each lexical concept to the PSE-S of its dominant sensory modality is measured as the PSE of the words multiplied by the modality exclusivity of the words. Hence, the average PSE-S score of each sensory modality is measured by the sum of the contribution of words dominant in the sense modality divided by the number of words, as shown in the following formula.

$$\text{PSE-S of sensory modality X} = \text{Sum [(PSE of WD)*(Ex of WD)]/Num. of WD}, \tag{2}$$

where PSE-S = perceived strength of embodiment of a sensory modality, WD = word dominant in the sensory modality X, and Ex = modality exclusivity.

To test the feasibility of the proposed formula (2) for the measurement of embodiment for sensory modalities, Zhong et al.'s (2022) sensorimotor norms for Chinese nouns were employed to calculate the PSE scores of the visual modality and the interoceptive modality. It is presumed that the visual modality differs from the interoceptive modality in imageability (i.e., the degree to which imagistic representations can be activated). Although whether imageability contributes to embodiment effects in word processing exclusively is still debated, it has been widely recognized that imageability is correlated with embodiment positively (e.g., Balota et al., 2004; Yap and Balota 2009; Connell and Lynott 2012; Zhong et al.,

2022). Thus, the proposed formula (2) would be empirically supported if the visual modality with higher imageability receives a higher PSE-S score than the interoceptive modality with lower imageability. As shown in Table 1, 215 nouns dominant in the visual modality and 290 nouns dominant in the interoceptive modality, extracted from Zhong et al.'s (2022) norms, were considered to calculate the PSE-S scores for the visual modality and the interoceptive modality, respectively[7]. A Mann–Whitney test shows that the visual modality has a significantly higher PSE score than the interoceptive modality (Mann–Whitney U = 22333.000, Z = −5.606, $p < 0.01$)[8]. This result confirms that the proposed PSE-S measurement for sensory modalities can differentiate modalities and model perceived degrees of embodiment as reported by intuition earlier.

Table 1
Mean value, standard deviation, and 95 % confidence interval of PSE-S scores for the visual modality and the interoceptive modality.

Modality	PSE-S score			*N*	Example
	Mean	SD	CI		
Vision	1.90	0.64	0.09	215	石头 *shi2tou* 'stone'
Interoception	1.59	0.52	0.06	293	哲学 *zhe2xue2* 'philosophy'

4. Methods

Zhao (2020) identified 199 synesthetic adjectives consisting of one sensory modality (e.g., 甜 *tian2* '[taste] sweet' and 甘甜 *gan1tian2* '[taste + taste] sweet') and 61 synesthetic adjectives combining different modalities (e.g., 醇厚 *chun2hou4* '[taste + vision] mellow') in Mandarin. Based on the synesthetic adjectives identified by Zhao (2020), Chen et al.'s (2019) modality exclusivity norms of Mandarin sensory adjectives include 71 synesthetic adjectives consisting of one sensory modality and 61 synesthetic adjectives combining different modalities. This study collected the modality exclusivity norms for the remaining 128 Mandarin synesthetic adjectives composed of one single modality[9].

To ensure the comparability and compatibility of this study's data with that of Chen et al. (2019), a similar method was used and an approximate number of participants with a similar language background were recruited to do the task.

Participants. 1046 Mandarin native speakers were invited to participate in the experiment. They were undergraduates or graduates in different universities in Mainland China, participating for course credits (mean age = 22.97, SD = 4.63).

Chen et al. (2019) recruited participants who were from Mainland China using simplified Chinese characters and outside Mainland China using traditional Chinese characters to do the rating task. However, the analysis of the collected data from the two types of participants showed no significant difference (Chen et al., 2019). Thus, this study only recruited Mandarin native speakers who did not major in linguistics but took Chinese language and culture as an elective course in Mainland China to collect the data.

Materials. Five questions for each adjective were used, such as 多大程度上,您可以通过(触觉/味觉/视觉/听觉/嗅觉)体验到(柔软)? *Duo1da4cheng2du4shang4, nin2ke3yi3tong1guo4(chu4jue2/wei4jue2/shi4jue2/ting1jue2/xiu4jue2)ti3yan4dao4(rou2ruan3)?* 'To what extent, can you experience (the soft perception) via (touch/taste/vision/hearing/smell/)?' The 640 questions generated from the 128 synesthetic adjectives were randomly split into 12 questionnaires.

For each questionnaire, a pre-test was carried out by five native Mandarin speakers in the lab under supervision to decide one question as the filter and one repetition question. The reason for setting filter and repetition questions is that although participants in the experiment were in attendance for the course credit, they were asked to complete the questionnaire by themselves, online, and anonymously. Hence, it is necessary to check whether the recruited participants did the online experiment carefully. During the pre-test, the five participants were asked to choose a number along the rating scale with six points (i.e., 0, 1, 2, 3, 4, 5) for the questions, of which 0 means 完全不可以 *wan2quan2bu4ke2yi3* 'totally cannot' and 5 means 完全可以 *wan2quan2ke2yi3* 'totally can' on the screen of a computer in our lab. The filter question and the repetition question were randomly chosen among the questions, receiving consistent scores in each questionnaire from the five participants. For example, the question involving the adjective 锐利 *rui4li4* 'sharp' experienced via touch was employed to be the filter question, as it was consistently rated as 5. Similarly, the question containing the adjective 明亮 *ming2liang4* 'bright' experienced via smell was chosen to be the repetition question, as it was consistently given a score of 1. In this way, each questionnaire had a filter question and a repetition question. Thus, there were 54 questions for each of the eight questionnaires

[7] Please note that Zhong et al. (2022)'s sensorimotor norms contain six sensory modalities for Chinese nouns (i.e., the Aristotelian five senses plus interoception). Thus, the maximal rating for a noun is the highest score received among the six modalities, and the modality exclusivity is calculated based on the ratings of all six modalities.

[8] This study employed nonparametric tests to compare independent data samples when the data did not pass either the normality test or the homogeneity of variance test. For detailed information about the Mann–Whitney test and the Kruskal–Wallis H test employed by this study, please refer to Gibbons and Chakraborti (2011).

[9] Mandarin adjectives combining different modalities (e.g., 醇厚 *chun2hou4* '[taste + vision] mellow') were considered to be synesthetic when they were used for the sense modalities that were not the combined modalities (e.g., 醇厚的歌声 *chun2hou4dege1sheng1* 'mellow song') by Zhao (2020). The usages are different from the commonly recognized synesthetic usages of Mandarin adjectives consisting of one single modality and have not been reported in other languages. Thus, Zhao et al. (2019a) and Zhao (2020) did not take into consideration the adjectives combining different modalities for the transfer pattern of linguistic synesthesia in Mandarin Chinese. This study also leaves this type of Mandarin adjective for future research.

and 55 questions for each of the four questionnaires. Ethics approval for the project was granted by the Research Ethics Committee from an affiliated organization.

Procedure. Participants were asked to answer the questions in one of the 12 questionnaires on the online platform Sojump[10]. Prior to the questions, a brief introduction to the five human senses and the task was provided. Participants were told that humans could see the colorful world through the visual faculty, hear a variety of sounds through the auditory faculty, experience the differences of temperature, texture, pain, and so on through the tactile faculty, taste the food through the gustatory faculty, and smell the odor through the olfactory faculty. In addition, they were also told that there were no right or wrong answers to the questions and that they could choose the answers via their intuition (0 meaning 完全不可以 *wan2-quan2bu4ke2yi3* 'totally cannot' and 5 meaning 完全可以 *wan2quan2ke2yi3* 'totally can'). The participants provided their informed consent before filling in their basic information (including demographic information and language background) and then answered the questions in the questionnaire. The task was self-paced and done by participants anonymously using their computers or phones. The whole task lasted eight to ten minutes, based on the results of the pre-test.

Data cleaning. This study generally followed Wang et al. (2019) to filter the invalid responses. In addition, the results of the pre-test were taken into consideration using the criteria of data cleaning as follows: (1) the whole completion time was less than four minutes, which indicated that the participants might not have considered the questions carefully; (2) the participants utilized one same number to answer all questions; (3) the difference between the responses and the scores received in the pre-test for filter questions was more than two (>2); and (4) participants rated the repetition questions with the number differences more than two (>2). For criteria (3) and (4), a threshold value of two was set because, on the six-point scale, a difference of more than two in the numbers would change the polarity of possibility. For instance, given that the perception conceptualized by the adjective 锐利 *rui4li4* 'sharp' experienced via touch was rated as 5 in the pre-test, responses smaller than 3 (i.e., 0, 1, or 2) were excluded, as these responses suggested a very low possibility of the perception experienced via touch, which was against common sense. In addition, all other responses of the participants who provided invalid answers for filter questions were also removed. Similarly, for the repetition question, people are supposed to answer the same questions with small differences. If participants gave scores of 1 and 4, for example, for the adjective 明亮 *ming2liang4* 'bright' experienced via smell, this could also indicate that the participants might not have considered the question carefully. All responses from those participants were also removed. The details for excluding invalid responses for each of the 12 questionnaires can be found in the Appendix.

After the data cleaning, the responses of 370 participants were removed and the responses of 676 participants were preserved. Thus, on average, each questionnaire received valid ratings from 56.3 participants. As shown in Table 2, the Cronbach's α for all 12 questionnaires is over 0.9. This indicates the high reliability of the collected data for Mandarin synesthetic adjectives.

Table 2
The Cronbach's α for the 12 questionnaires after data cleaning.

Questionnaire No.	Cronbach's α	Questionnaire No.	Cronbach's α
1	0.932	7	0.949
2	0.949	8	0.932
3	0.916	9	0.952
4	0.958	10	0.962
5	0.949	11	0.944
6	0.916	12	0.912

5. Results

This study employed a similar data collection procedure and recruited a similar number of participants as Chen et al. (2019). Thus, the sensory ratings of the 128 synesthetic adjectives collected by this study can be combined with those of the 71 synesthetic adjectives by Chen et al. (2019) for the modality exclusivity norms of all the 199 Mandarin synesthetic adjectives identified by Zhao (2020). The modality exclusivity norms of the Mandarin synesthetic adjectives, with the dimension of the PSE score added, can be accessed at: https://bit.ly/37Lw4Ew.

Table 3 presents the average sensory ratings for the five senses, which are derived from the 199 Mandarin synesthetic adjectives. The visual sense has the highest rating score (i.e., 2.78), and the olfactory sense has the lowest (i.e., 1.40). This pattern is similar to that of general sensory adjectives in Mandarin found by Chen et al. (2019).

Table 3
Mean sensory rating, standard deviation, and standard error per sense of Mandarin synesthetic adjectives.

Modality	Mean	SD	SE
TOUCH	2.40	1.53	0.11
TASTE	1.96	1.35	0.10
VISION	2.78	1.11	0.08
HEARING	2.07	1.19	0.08
SMELL	1.40	1.00	0.07

[10] Sojump is a widely used online platform to collect data using questionnaires in Mainland China, with access at: https://www.wjx.cn.

5.1. PSE-S scores of sensory modalities

The PSE-S scores of the five sensory modalities were calculated based on the modality-dominant adjectives. For instance, the adjective 冰冷 *bing1leng3* 'ice-cold' was rated 4.78 out of 5 in touch, 2.81 in taste, 2.39 in vision, 2.11 in hearing, and 1.63 in smell. Hence, the modality exclusivity of this adjective is 0.23, and its PSE score is 8.46, with touch being the dominant modality. Among the 199 Mandarin synesthetic adjectives, 68 adjectives are dominant in touch, 25 adjectives in taste, 67 adjectives in vision, 35 adjectives in hearing, and four adjectives in smell.

Table 4 shows the lexical concepts with the highest and the lowest PSE scores for each dominant sensory modality. To interpret the PSE data, such as those presented in Table 4, it is important to bear in mind that these are the perceived strengths of embodiment of lexicalized concepts and not of the specific cognitive properties that they represent. As such, they should reflect the language-dependent process of lexicalization. The keyword "perceived" in PSE underlines the fact that this is a measurement of the result of lexicalization and is bound to show some language-dependent differences. Two quick observations give affirmation to the validity of the proposed measurement. The first is that the olfactory sense shows the smallest range of PSE. This very likely directly reflects the cross-lingual trend of a significantly smaller number of olfactory words (e.g. Levinson and Majid 2014). The second is that the lexical concepts with the lowest PSE seem to all represent the lower end of the scalable sensory property (e.g. weak taste, low voice, unclear vision), but not necessarily the unpleasant ones.

Table 4
The lexical concepts with the highest and the lowest PSE scores for each sensory modality.

Dominant modality	The lexical concept with the highest PSE score	The lexical concept with the lowest PSE score
TOUCH	柔 *rou2* 'soft' (PSE = 8.78)	脆弱 *cui4ruo4* 'fragile' (PSE = 3.80)
TASTE	酥 *su1* 'crisp' (PSE = 8.46)	温润 *wen1run4* 'moist' (PSE = 5.37)
VISION	清晰 *qing1xi1* 'clear' (PSE = 8.37)	软弱 *ruan3ruo4* 'feeble' (PSE = 3.28)
HEARING	强 *qiang2* 'strong' (PSE = 8.94)	沉静 *chen2jing4* 'quiet' (PSE = 3.97)
SMELL	香*xiang1* 'fragrant' (PSE = 7.34)	清爽*qing1shuang3* 'clear' (PSE = 6.49)

Table 5 demonstrates the PSE-S scores for the five senses calculated based on the PSE of lexical concepts dominant in the sensory modality. As shown in Table 5, the PSE-S score for taste is the highest (i.e., 2.62), and the PSE-S score for hearing is the lowest (i.e., 1.77). The Mann–Whitney tests show that there are significant differences between taste and touch (Mann–Whitney U = 590.000, Z = −2.249, $p < 0.01$), between taste and vision (Mann–Whitney U = 540.000, Z = −2.607, $p < 0.01$), and between taste and hearing (Mann–Whitney U = 258.000, Z = −2.684, $p < 0.01$). However, no significant difference is observed between touch and vision (Mann–Whitney U = 1996.000, Z = −1.239, $p = 0.215$), between touch and hearing (Mann–Whitney U = 935.000, Z = −1.772, $p = 0.076$), and between vision and hearing (Mann–Whitney U = 1073.000, Z = −0.698, $p = 0.485$)[11].

Table 5
Number of adjectives per dominant modality, mean sensory ratings and PSE-S scores for the five senses.

Dominant modality	The mean rating for the five senses					PSE-S score	*N*
	TOUCH	TASTE	VISION	HEARING	SMELL		
TOUCH	**4.04**	1.86	2.62	1.68	1.08	2.02	68
TASTE	1.26	**4.52**	1.70	1.26	2.67	2.62	25
VISION	1.74	1.30	**3.67**	2.02	1.15	1.90	67
HEARING	1.41	1.42	2.29	**3.57**	1.25	1.77	35
SMELL	1.23	3.44	1.76	1.30	**4.26**	2.23	4

Recall that the mapping directions of linguistic synesthesia in Mandarin, except the mapping between touch and taste, show preferences between the senses (e.g., the touch-to-vision and vision-to-hearing directional preferences) (see Fig. 1, Zhao et al., 2019a). However, the directional preferences between the sensory modalities and the perceived strengths of embodiment do not necessarily match based on the PSE-S scores of the modalities. Thus, the statistical results can only suggest that taste is perceived to be more embodied than touch/vision/hearing in the sensory lexicon of Mandarin, as taste shows a significantly higher PSE-S score than touch/vision/hearing[12]. However, the results do not support the hypothesis of embodiment asymmetries of sensory modalities that touch is the most embodied, followed by taste and smell, and vision and

[11] The statistical test cannot be applied to the olfactory sense, as it only contains four adjectives.

[12] Note that taste with the highest PSE-S score does not contradict the mapping directionality of linguistic synesthesia in Mandarin (see Fig. 1), where taste occupies the same position as touch acting as the source of synesthetic mappings. Nevertheless, apart from the embodiment asymmetries between taste and the two modalities of vision and hearing, all other hypothesized embodiment asymmetries between sensory modalities cannot be supported by the PSE-S scores.

hearing are the least embodied, which was proposed by the studies such as Shen (1997), Shen and Cohen (1998), and Yu (2003). In addition, taste with the highest PSE-S score contradicts the assumption that touch is the most embodied, as argued by Shen (1997) and Popova (2005). It is important to note that this study's proposed measurement of embodiment takes into account and integrates all instances of lexical uses in a specific sensory modality by considering the modality exclusivity, which includes when the sensory word is used in a non-dominant modality. In other words, the proposed measurement considers all possible instances of that particular modality, while the previous proposal, including the intuition-based reports, focused on the dominant uses. Thus, the hypothesis that sensory modality embodiment asymmetries determine the mapping directions of linguistic synesthesia is not fully supported by the empirical data of this study, and an alternative account is needed.

5.2. Sensory polysemy and PSE scores of sensory concepts

Sensory words often represent meanings in more than one sensory modality, which is due to linguistic synesthesia or other means of lexical changes (e.g., Chen et al., 2019; Zhao et al., 2022). In this section, we explore the directional relation of conceptual mappings between the perceived strengths of embodiment of the 199 Mandarin synesthetic adjectives. Zhao et al. (2022) divided the synesthetic adjectives into four groups according to the number of sensory modalities in which the adjectives were used. In addition, the 99 non-synesthetic sensory adjectives from Chen et al. (2019), representing a single sensory modality, form the fifth group of one-sensory-modality words for this study.

Table 6
Mean value, standard deviation, and 95 % confidence interval of PSE scores for Mandarin sensory adjectives used for different numbers of sensory modalities.

Adjective type	PSE score			*N*	Example
	Mean	SD	CI		
Used for five senses	7.50	0.67	0.82	6	清 *qing1* 'limpid'
Used for four senses	7.09	0.84	0.39	20	涩 *se4* 'astringent'
Used for three senses	6.90	1.23	0.37	45	滑 *hua2* 'smooth'
Used for two senses	6.28	1.14	0.20	128	小 *xiao3* 'small'
Used for one sense	5.37	1.56	0.31	99	响 *xiang3* 'loud'

Table 6 shows the average PSE scores of Mandarin sensory adjectives according to the number of sensory modalities they represent. A general pattern emerges: adjectives used for more sensory modalities are perceived to be more embodied. The adjectives used for five sensory modalities have the highest PSE score (7.50), followed by those used for four, three, and two modalities in descending order. The adjectives used for a single sensory modality, i.e., non-synesthetic adjectives, have the lowest PSE score (5.37). The statistical tests reveal that there are significant differences between the adjectives used for one sensory modality and the other four types of adjectives (Kruskal–Wallis $H = 54.656$, $p < 0.01$). In addition, significant differences in the PSE scores are also observed between the adjectives used for two sensory modalities and the adjectives used for five sensory modalities (Mann–Whitney $U = 138.000$, $Z = -2.647$, $p < 0.01$), between the adjectives used for two sensory modalities and the adjectives used for four sensory modalities (Mann–Whitney $U = 737.000$, $Z = -3.046$, $p < 0.01$), as well as between the adjectives used for two sensory modalities and the adjectives used for three sensory modalities (Mann–Whitney $U = 2015.000$, $Z = -2.993$, $p < 0.01$). Thus, the PSE can differentiate perceived strengths of embodiment among sensory adjectives according to the number of sensory modalities they represent.

Although the perceived strength of embodiment does not attest to a modality-based embodiment hierarchy for linguistic synesthesia, it does show a hierarchy of embodiment of lexical concepts according to differences in perceptual experiences. Crucially, synesthetic adjectives are perceived to be more embodied than non-synesthetic adjectives. In other words, it can be assumed that adjectives with a higher embodiment are more likely to have synesthetic mappings. In addition, among the synesthetic adjectives, the adjectives used for five/four/three sensory modalities are perceived to be more embodied than the adjectives used for two sensory modalities. The significance of these results will be discussed below.

6. Discussion

We have discussed the theoretical implications and ramifications of the PSE-S and PSE results reported in this paper. Similar to and reinforcing several recent studies on mapping directionalities of linguistic synesthesia in several languages (e.g., Fishman 2022; Zhao et al., 2022), our PSE-S data shows that there is no strict hierarchy among sensory modalities according to their perceived strengths of embodiment. In other words, an *a priori* embodiment asymmetries among sensory modalities for sensory words are not attested. On the other hand, the PSE scores of lexical concepts show a clear embodiment asymmetry based on different perceptual experiences. That is, richer perceptual experiences, as measured by the number of sensory modalities associated with a sensory word, are generally perceived to be more embodied. Although seemingly similar, this generalization fundamentally differs from the earlier modality-based asymmetry proposal in that it does not

require an *a priori* and non-verifiable assignment of every sensory adjective to a specific sensory modality. What it assumes is simply the verifiable qualia knowledge of how each sensory word is used in terms of sensory meanings. Given the high frequency of linguistic synesthesia, the predominance of polysemy across different modalities of sensory words, and the significant variations of meanings of sensory words across different languages, an assignment of each lexical concept to a specific sensory modality presupposes several yet-to-be-verified assumptions. As such, the current generalization requires no further presuppositions and should be the more desirable theory by Occam's razor. In addition, the current generalization also follows the theoretical definition of embodied cognition, in that each sensory concept perceived by a bodily faculty is embodied.

Note also that the generalizations presented in this paper are compatible with a lexical concept-based constraint on the asymmetry of directionality for linguistic synesthesia (e.g. Zhao et al., 2022). Zhao et al. (2022) found that, when examining linguistic synesthesia at the lexical level, the mapping directionality is determined by the combinations of lexical concepts rather than a modality-based general direction, which can be formulated by different Mapping Principles (MP) in conceptual metaphors (Ahrens 2002, 2010). For example, the linguistic synesthetic expression 烈酒 *lie4 jiu3* 'strong wine' follows the MP that the wine tastes strong like fire has strong heat (tactile "heat" to gustatory "strong"), while 腰酸 *yao1 suan1* 'the waist feels sore' follows the MP that the waist feels as bad as sour things taste bad (gustatory "sour" to tactile "pain"). That is, the mapping directionality is not determined by the sensory modality but by MPs defined based on lexical concepts.

To verify whether the PSE can predict the mapping directionality of the asymmetry for linguistic synesthesia, further examination of the mapping directions of linguistic synesthesia on Mandarin compound adjectives, a different dataset that is distinct from the lexical adjectives reported earlier, is conducted. Compounding is the most productive morphological device for word formation in Mandarin Chinese (Chao 1968; Li 2022; Song et al., 2022). Zhao et al. (2019b) reported that linguistic synesthesia was involved within a compound adjective in Mandarin, in which the concept of one adjectival constituent in one sensory modality was mapped to the concept of the other adjectival constituent in a different modality. Take the compound adjective 鲜亮 *xian1liang4* 'Lit. tasty-bright; bright' for example: the gustatory concept 鲜 *xian1* 'tasty' maps to the visual concept denoted by 亮 *liang4* 'bright.' Mandarin compounds offer an interesting data set for linguistic synesthesia, as both the source and target sensory modalities are lexically realized.

Fifty-one synesthetic compounds were collected to examine the prediction power of the PSE by comparing the PSE of the source sensory adjective with the PSE of the target sensory adjective, based on the empirically obtained PSE data reported earlier[13]. Recall that a PSE-based embodiment asymmetry account predicts that the source sensory adjective should have a higher PSE than the target sensory adjective for synesthetic compounds. Table 7 shows that 42 of the 51 compound adjectives are consistent with the prediction. For instance, 酸痛 *suan1tong4* 'Lit. sour-painful; sore' with the gustatory concept of 酸 *suan1* 'sour' (PSE = 7.53) maps to the tactile concept of 痛 *tong4* 'painful' (PSE = 5.86). On the other hand, nine of the 51 compounds are composed of a target sensory adjective with a PSE higher than that of the source. For instance, the adjective 苦寒 *ku3han2* 'bitter cold' has the gustatory concept of 苦 *ku3* 'bitter' (PSE = 6.44) mapping to the tactile concept of 寒 *han2* 'cold' with a higher PSE (PSE = 7.47). Note that both compounds involve mapping from the proposed less embodied modality (i.e., taste) to a more embodied modality (i.e., touch) and cannot be predicted by the intuitive modality-based embodiment asymmetry account.

Table 7
Mandarin compound adjectives and perceived strengths of embodiment.

Compound adjective	*N*	Example
Source PSE > Target PSE	**42 (82.4 %)**	酸痛 *suan1tong4* 'Lit. sour-painful; sore'
Target PSE > Source PSE	9 (17.6 %)	苦寒 *ku3han2* 'bitter cold'
Total	51 (100 %)	–

Contrary to the intuitive modality-based asymmetry account that makes a sweeping prediction of all adjectives of the same modality, the lexical concept-based asymmetry account makes a prediction based on the relative position of the PSEs of two components of the compound. On one hand, this follows the fact that compounding is a lexical process involving two lexical concepts and requires no further stipulations. On the other hand, since PSE values are empirically obtained, standard errors will also be accounted for. That is, this account makes no prediction when the gap between two lexical concepts is smaller than the combined standard errors of them. Thus, the Standard Errors (SE) of each PSE-S (TASTE: 0.15; SMELL: 0.19; TOUCH: 0.14; VISION: 0.14; HEARING: 0.19) are considered to narrow down to focus only on valid predictions. We found one compound (i.e., 清凉 *qing1liang2* 'cool') with a PSE difference lower than the combined standard errors. That is, the difference of the two lexical PSEs, 8.20 and 8.23 respectively, is 0.03 and smaller than the sum of the SEs of the two sense modalities (0.14 each). Excluding this example, the lexical PSE-based account of embodiment asymmetry has a high recall of 98.0 % (50/51), with 84 % (42/50) precision and 16 % (8/50) error. In contrast, the traditional intuitive modality-based account (i.e., Shen and

[13] To avoid the controversial issue of determining a compound word, this study adopted a well-established and commonly used Chinese dictionary *Xiandai Hanyu Cidian* (7th edition) (Institute of Linguistics, CASS 2016) to collect the Mandarin compound adjectives. The whole collected data can be accessed at https://bit.ly/37Lw4Ew.

colleagues' model) has a high error rate of 41.2 % (21/51). In sum, the PSE score provides a robust tool for empirical decision of degrees of embodiment and can predict the directional asymmetry of linguistic synesthesia. It provides further support for the lexical concept-based account for linguistic synesthesia by Zhao et al. (2022).

Additionally, the PSE-based embodiment asymmetry at the lexical conceptual level found in this study is compatible with the results of two recent experimental studies on the comprehension of linguistic synesthetic expressions in English by Fishman (2022) and Zhong et al. (2024). Fishman's (2022) study found that the directional preferences of linguistic synesthesia were mediated by lexical factors, rather than the properties of sensory modalities. In addition, the study by Zhong et al. (2024) found that novel synesthetic expressions following the direction that was congruent with the direction generalized based on the corpus data by Strik Lievers (2015) (e.g., from touch to hearing) were judged to be more common, more appropriate, easier to comprehend, and more literal than those with a reverse direction. That is, Zhong et al. (2024) found that familiarity based on conventionality, another lexical conceptual property, played a role in the processing of the directionality of linguistic synesthesia. These two studies provide further support, based on English data, for a lexical concept-based account of the perceived embodiment asymmetry and its role in determining the directionality of linguistic synesthesia. They also provide evidence to further explore the roles of other lexically encoded perceptual experiences, in addition to the strong effects of the PSE reported in this study.

7. Conclusion

We laid the groundwork for this study by underlining the fact that there has been no clear consensus on the nature of the representation of embodied cognition in the field. The emerging consensus is instead that the strongest and the weakest forms of the theory are not empirically supported and that a more interactive theory as well as associated tools to measure degrees of embodiment, are needed. Given that it is not yet possible to directly measure and verify the degrees of embodied cognition, we hypothesized that the observed asymmetry facts were due instead to the commonly shared perceived strength associated with each modality.

This study employed empirical behavioral data obtained through the sensory rating tasks on synesthetic adjectives to test the hypothesis of embodiment asymmetries of sensory modalities. Based on the modality exclusivity norms, an empirical model of the Perceived Strength of Embodiment (PSE) was proposed to measure the perceived strength of embodiment of lexical concepts and sensory modalities. Synergizing recent studies, it was found that an *a priori*, intuition-based assignment of embodiment asymmetries of sensory modalities did not reliably predict the mapping directions of linguistic synesthesia and that the proposed strengths of embodiment assigned to the sensory modalities could not be independently verified[14]. Our study found instead that the lexical conceptual properties of sensory adjectives, especially those related to perceptual experiences, appeared to show an asymmetry of the perceived embodiment, such as synesthetic vs. non-synesthetic adjectives, as well as adjectives conceptualizing more sensory modalities vs. those conceptualizing fewer modalities. In addition, this study demonstrated that with a separate set of data involving Mandarin compounds, a PSE-based account reliably predicted the directionality of linguistic synesthesia. Thus, our study supports a perceptual experience-driven lexical concept-based account of the embodiment asymmetry for linguistic synesthesia.

The modality exclusivity norms of Mandarin synesthetic adjectives reported in this study will facilitate experimental lexical processing research for Mandarin Chinese, similar to the previously available modality exclusivity norms that have been crucial for selecting stimuli in psycholinguistic experiments in the past (Lynott et al., 2020; Speed and Brysbaert 2021). In addition, our new quantifiable empirical model defining PSE and PSE-S is a new tool for empirical studies of embodied cognition, including but not limited to linguistic synesthesia and other types of metaphors in different languages. For instance, the concept of embodiment also features prominently in one of the most fundamental and long-lasting debate in the study of language: what are nouns and verbs and why are they the essential categories in human language. Some recent studies on the sensory lexicon have shed lights on this issue (e.g. Strik Lievers and Winter 2018; Zhong et al., 2023). The perceived degree of embodiment measurement provides a new tool to explore embodiment and concreteness as the foundation of categorical differences.

Lastly, the differentiation of perceived strengths of embodiment and (*a priori*) assigned strengths of embodiment theoretically resolve issues raised by the recent challenges to the theoretical ramifications of previous proposals to assign strengths of embodiment to modalities (e.g., Rakova 2003; Winter 2019). This study argues that the differences in the degrees of embodiment are perceived and induced by the conceptualization of perceived experiences through lexicalization, instead of *prima facie* by the purported embodied nature of sensory modalities. This conceptualization of the perceived strength of embodiment lays the foundation for an empirical approach to determine the strength of embodiment based on existing norms collected through behavioral studies. The PSE-based results reported in this paper are consistent with recent findings that the mapping directionality of linguistic synesthesia is constrained by lexical factors (e.g., Winter 2019; Fishman 2022),

[14] In fact, we find that the PSE-S scores of the five sense modalities are consistent with the distribution of inter-modality synesthetic mappings that vary in different languages, and that cultural heritages (i.e. shared perceptual experiences) may play a role in the PSE-S in each language. This is an issue that is beyond the scope of the current paper and will be addressed in a separate paper in preparation.

and by the Mapping Principles (MPs) underlying lexical concepts (e.g. Zhao et al., 2022; Zhong et al., 2024). Thus, this study provides new evidence for embodied cognition and furthers the understanding of how linguistic conceptualization of sensory perceptions encodes embodiment.

Declaration of competing interest

None.

CRediT authorship contribution statement

Chu-Ren Huang: Supervision, Conceptualization. **Qingqing Zhao:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Kathleen Ahrens:** Visualization, Conceptualization. **Zhao Wang:** Formal analysis, Data curation. **Yunfei Long:** Software, Formal analysis.

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Data availability

The data can be accessed at: https://bit.ly/37Lw4Ew.

Appendix

The exclusion details for each of the 12 questionnaires.

Questionnaire No.	Total responses	Invalid responses (1)	Invalid responses (2)	Invalid responses (3)	Invalid responses (4)
1	85	0	0	12	16
2	90	0	2	17	15
3	90	1	2	20	13
4	92	0	0	15	13
5	88	0	0	16	16
6	85	0	0	20	9
7	87	0	0	13	14
8	86	1	2	8	20
9	86	1	0	13	18
10	83	0	0	19	14
11	86	2	0	14	14
12	88	0	1	18	11

*Invalid responses (1) mean the responses excluded based on criterion (1): the whole completion time was less than four minutes.
Invalid responses (2) mean the responses excluded based on criterion (2): the participants utilized the same number to answer all questions.
Invalid responses (3) mean the responses excluded based on criterion (3): the difference between the responses and the scores received in the pre-test for filter questions was more than two.
Invalid responses (4) mean the responses excluded based on criterion (4): participants rated the repetition questions with differences of more than two.

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