Sensorimotor norms for Chinese nouns and their relationship with orthographic and semantic variables

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Sensorimotor information is vital to the conceptual representation of our knowledge system, as is evidenced by recent studies that examined perceptual strength via modality exclusivity norms across a variety of languages. This study takes previous work a step further by collecting data for the perceptual and action norms for 664 disyllabic nouns among 438 native speakers and creating the first and largest dataset of sensorimotor norms for nouns in Chinese. Using aggregated semantic covariates, including concreteness ratings from a concreteness rating study, as well as the reaction times and error rates from a lexical decision study, our current work demonstrates the strengths of sensory modalities and action effectors in Chinese nouns and explores the contributions of embodied experiences in reflecting orthographic representations and semantic processing in the Chinese language. This study contributes valuable data sources to for the study of Chinese lexical processing and highlights the importance of sensorimotor information and embodied manifestations in the semantic representations of concepts. Our results also support the unifying concept of orthographic awareness in lexical processing and reading, instead of the traditional phonological and semantic awareness.

Keywords: sensorimotor norms; embodied cognition; orthography; lexical decision; Chinese nouns

Introduction

A wealth of psychological and neuroscientific research argues for the representational nature and organisation of concepts of a language. The traditional view sees language as a symbol manipulation system that conveys meaning through amodal and arbitrary symbols (e.g. Collins & Loftus, 1975; Levelt, 1989), but in work in the past twenty years, conceptions of linguistic processing established on bodily experiences have become more dominant (e.g. Barsalou, 1999; Gallese & Lakoff, 2005; Gibbs, 2006; Jirak et al., 2010; Wilson, 2002; Zwaan & Taylor, 2006). The latter view is generally termed "grounded cognition," capturing a broad scope of grounding mechanisms for the interconnections among the perception, action, and cognitive systems. A related, yet narrower concept, "embodied cognition," emphasizes the role of the bodily experiences as an important grounding mechanism in reflecting cognitive representations (see, e.g. Barsalou, 2008; Barsalou, 2010). Specifically, embodied cognition views lexical representations as grounded in sensorimotor brain areas dedicated to perception and action. Thus, processing semantic meanings involve recruiting modality-specific and action effector-specific networks that distribute across the cortex (Mahon, 2015; Pezzulo et al., 2013). In other words, embodied language theories postulate that experiential traces stored in modality-(and action-)specific brain areas are activated by encountering different words and that these activations in the brain will contribute to the semantic representations of lexical items in human languages.

To study the link between sensorimotor information and the semantic processing of words, it is essential to operationalise modality-(and action-)specific knowledge in a word or concept. A line of behavioural studies discussing the impact of perceptual strength on word processing in different sensory modalities has provided important insight into this correlation. The perceptual strength norms, or modality exclusivity norms, were first started in English by Lynott and Connell (2009, 2013) and have been extended to other languages, including

Chinese (Chen et al., 2019), Dutch (Speed & Majid, 2017), French (Chedid et al., 2019; Miceli et al., 2021), Italian (Morucci et al., 2019; Vergallito et al., 2020), and Russian (Miklashevsky, 2018). These norms have typically been collected by asking people how strongly they experienced a concept through each Aristotelian sensory modality, i.e. *seeing*, *hearing*, *tasting*, *smelling*, or *touching/feeling*. This line of research taps into the strength of specific modalities in the conceptual processing of words and thus unveils the (in)significance of sensory perception as a concept and seeks to understand if the concept is more unimodal or multimodal.

Nevertheless, modality-specific information is not the full picture of how sensorimotor information is activated and represented by the knowledge system—action effector-specific experience is equally pivotal in acquiring perceptual information of the environment. For example, sometimes, the real texture of an object is not realised unless a person reaches out their arms and uses their hands to touch the surface of the object. The movement of body parts generates a wealth of perceptual information, similar to modality-specific measures. Additionally, Lynott et al.'s (2020) recent study of sensorimotor strength norms for 39,707 concepts in English collected action strength across five bodily effectors, *foot/leg, hand/arm, head excluding mouth, mouth/throat*, and *torso*, in addition to the traditional five-sense vectors. Dominant effectors and effector exclusivity were assigned to each word, following the paradigm used in the modality exclusivity studies. Moreover, *interoception*, a physiologically distinct category of perceptual experience related to the awareness of the signals coming from the body (Connell et al., 2018), was also examined. In contrast to other Aristotelian sensory modalities that detect stimuli from the external environment, interoceptive sensations mainly associate with visceral senses (e.g. cardiovascular, respiratory, gastrointestinal, bladder) and awareness of internal bodily states (e.g. hunger, thirst, temperature, itch, tickle, sensual touch, painful sensations) (Cameron, 2002; Craig, 2002, 2003). The augmentation and consolidation of perception and motion in this large-scale norming study demonstrate a more detailed picture, which depicts how the specific sensorimotor information is encoded in the language.

Thus far, although perceptual ratings are available in many languages, the inclusion of motor strengths as well as interoception ratings is only available in English. To firmly establish as a fact in human cognition the relationship between embodied experiences and the semantic processing of linguistic representations, evidence from languages that differ typologically from English is essential. Thus, Chinese is an apt candidate for its distinctive morphological structures and orthographic features compared to Indo-European languages (e.g. Huang & Hsieh, 2015). In this study, we begin by presenting sensorimotor norms for Chinese nouns, which is done by replicating the procedures in Lynott et al. (2020). Then, we discuss their relations with one particular aspect of the Chinese language, i.e. semantics as the orthographically relevant level for the Chinese writing system, as orthography constitutes a significant factor in word recognition and processing (e.g. Tsang et al., 2017). Furthermore, we incorporate reaction times (RTs) and error rates (or accuracy) in a word recognition task to reveal possible intersections between sensorimotor strength and semantic processing of word representations. The pivotal question asked in this paper is, under the theories of grounded cognition and embodied cognition, to what extent does sensorimotor information manifest lexical representations (i.e. word writing forms) and predict word processing behaviour (i.e. word recognition latencies) in Mandarin Chinese.

Orthographic representations of linguistic and sensorimotor systems

The theory that linguistic expressions and processing are built upon bodily experience can be traced back to the concept of qualia by Aristotle in Greek philosophy. More recently, Pustejovsky’s (1995) theory of Generative Lexicon (GL) relies on the organisation of the qualia structure to account for the systematicity and versatility of lexical meanings. Both presuppose at some level the lexicalisation of sensorimotor concepts in order to encode and represent bodily experiences or to ‘embody’ non-bodily experiences.

The Chinese writing system provides an unique window as to how bodily experiences are lexically encoded as semantics and is the “orthographically relevant level (ORL)” for the character-based (Hanzi) Chinese writing system, instead of phonology as ORL for most other languages (Huang & Hsieh, 2015; Sproat, 2000). This level of linguistic representation of Chinese characters has been shown to be a conventionalised human concept system that is richly structured and has been used continuously for over three millennia (e.g. Chou & Huang, 2010; Huang et al., 2013a; Huang et al., 2013b). Previous studies posed that the unique glyphs, i.e. semantic radicals, which imply the meaning of characters in the Hanzi writing system, may signify connections between Chinese characters and their representative semantic meanings. Moreover, radicals that pertain to more embodied human experiences are more productive than other glyphs in deriving characters in the Chinese writing system.

In addition to the generally obligatory semantic radicals, it is estimated that over 70% of Chinese characters also contain a component indicating the pronunciation of a character (Lee et al., 2015). This component, conventionally referred to somewhat misleadingly as a phonetic symbol, marks phonological relatedness instead of actual pronunciation (e.g. Huang et al., 2022). Past studies showed that the phonetic symbols only provide valid cues in at most 50% of the semantic-phonetic characters in Mandarin Chinese (Hsiao & Shillcock, 2006). However, it is important to note that the accuracy of these phonological representations cannot be calculated as there is no reliable way to assign phonological values to these phonetic symbols. It is safe to assume based on past studies (such as Hsiao and Shillcock, 2006) that phonological values will be accurate less than 50% of the time.

Lee and Huang (2022) argued that ORL plays a central role in the intriguing inconsistency in past Mandarin-based studies on phonological awareness in reading. They noted that, unlike the vast majority of other writing systems in the world, phonology plays a minor role in Chinese orthography and that the inconsistent results reported in studies on phonological awareness in reading Chinese character reading are anomalies in contrast to consistent results in other languages. In addition, several recent studies showed that phonological awareness is better predicted by the acquisition of phonological writing systems (e.g., Pinyin romanisation). Thus, they argued that what has been reported as ‘phonological awareness’ is, in fact, an instantiation of orthographic awareness. More specifically, it is the awareness of the underlining relevant linguistics generalisations encoded by the writing system. For languages with phonology as the ORL of their writing systems, phonological awareness and orthographic awareness make the same prediction. However, with semantics as the ORL for Hanzi character orthography, Chinese can provide crucial evidence as phonological awareness and orthographic awareness will make different predictions. Thus, the current study aims to provide evidence supporting the hypothesis of orthographic awareness by showing the relevance of semantics in Chinese lexical processing.

Apart from the orthographic radicals, formation rules of characters also imply visual and/or auditory cues of Chinese characters. Chinese writing forms generally fall into six types, following *Shuowen Jiezi* (Xu, 1963):[1] pictographs, ideographs, compound ideographs, phono-semantic compounds, phonetic loan characters, and derived cognates. Pictographs, literally translated as “resembling the form,” represent the visual image of the concrete objects. For example, the character 日 *rì* ‘sun’ comes from a simple depiction of the sun by drawing a circle with a dot inside. Ideographs, known as “indicating the matter,” are mainly used to describe abstract concepts. For example, 上 *shàng* ‘up,’ is composed of two lines, with the longer horizontal line indicating the surface, whereas the upper shorter line indicates

[1]*Shuowen Jiezi* 说文解字 is the first dictionary of lexical etymology of Chinese characters by Xu Shen in the Han Dynasty in 121 AD. The version cited is a reprint.

what is above; and with its antonymy, 下 *xià* 'down,' the upper longer line indicates the surface while the shorter line indicates what is below. The third type, compound ideographs, is a combination of two ideographs or pictographs. For instance, the character 泪 *lèi* 'tear' consists of a 氵 (water radical) and a 目 *mù* 'eye.' Together, they depict an image of water in the eyes, and thus represent tears. The phono-semantic compounds are those characters that are comprised of both the phonetic and semantic radicals, which is the predominant word form in Chinese and accounts for more than 80% of all Chinese characters (Law et al., 2005). For instance, the character 清 *qīng* 'clear' has a semantical radical on the left (i.e. 氵 'water') and a phonetic symbol on the right (i.e. 青 *qīng*), denoting the pronunciation of this character, and the original meaning of 清 *qīng* 'clear' describes the limpidity of water. Note that most phonetic compounds have a left-right structure—the semantic radical is on the left while the phonetic symbol is on the right (Hsiao & Shillcock, 2006). The last two types—phonetic loan characters and derived cognate—are controversial and rare, therefore, they are often omitted in the modern Chinese writing system.

Among the four major types of Chinese characters, pictographs, ideographs, and compound ideographs all provide cues of the meaning of a character, while phono-semantic type typically combines two types of information in phonetic and semantic components. That is to say, visual semantic cues will be diluted in phono-semantic type characters compared to the other three types. The role of orthography was investigated in Chen et al.'s (2019) Chinese modality exclusivity norms, in which they found that pictographs, ideographic, and ideographic compounds were salient for visual, gustatory, olfactory, and tactile dominant modalities. On the contrary, pictographs were not found in the auditory dominant modality, but phono-semantic compounds were more prominent in concepts that were more related to the auditory sense.

Under the embodied view, with semantics as the ORL for Chinese writing, and with the hypothesis of orthographic awareness in reading and lexical processing, we expect sensorimotor information to be reflected in orthography, which can be attested in reading and processing of Chinese characters. More specifically, we propose two hypotheses with respect to the relation between sensorimotor information and orthography as well as the relation between sensorimotor information and lexical processing. We first introduce the two sub-hypothesis involving orthography and sensorimotor information. The second hypothesis will be provided in the following section.

H1a: Semantic radicals can serve as an orthographic signal of the dominant sensorimotor dimension. *For* example, if a character contains an "eye" radical, its dominant perceptual modality should mostly lean towards the visual sense. Similarly, if a character contains a "foot" radical, its dominant action effector most likely falls into the foot/leg rather than other bodily action effectors.

H1b: Formation types can serve as an orthographic signal for the dominant sensorimotor dimension. Notice that although formation rules of Chinese characters rely on visual cues primarily (i.e. pictographs, ideographs, and compound ideographs; see, e.g. Yang & Wang, 2018), a significant sub-set also employs auditory cues in the form of phonetic symbols. As such, we expect that the characters containing phonetic cues (i.e. phono-semantic compounds) likewise feature prominently among characters with auditory sense as their dominant sense.

Semantic processing and sensorimotor system

It is widely evidenced in the literature that semantic variables, such as word frequency, age of acquisition (AOA), concreteness, and imageability are influential factors across a variety of visual word recognition tasks (e.g. Balota et al., 2004; Brysbaert et al., 2018; Chumbley & Balota, 1984; Cortese & Khanna, 2007; Paivio et al., 1968; Schock et al., 2011; Yap &

Balota, 2009). Among all these variables, concreteness and imageability are two robust predictors that can predict latencies in distinguishing words from non-words in lexical decision tasks (e.g. Balota et al., 2004; Brysbaert et al., 2014; Paivio et al., 1968). Specifically, words perceived as more concrete and more imageable will be processed relatively faster and more accurately than their abstract and less imageable counterparts. Of note, both concreteness and imageability overlap with sensory features to a large extent. In concreteness studies, concreteness is indicated as words that can be perceived through our sensory input, whereas abstract words are those that cannot be experienced directly by the human senses but are defined through linguistic input (Brysbaert et al., 2014; Xu & Li, 2020). Similarly, imageability is also related to the ease of accessing a mental image stimulated by our sensory experiences, such as visual and auditory inputs (e.g. Paivio et al., 1968). On occasion, concreteness has even been treated no differently than imageability. For example, one of the most influential theories in explaining concreteness effects in word processing performance—dual-coding theory—suggests that concrete concepts directly activate verbal and imagistic representations, whereas abstract words only connect to images via other verbal codes (Paivio, 1990). Abstractness is not equivalent to low imageability despite the high correlation between the two concepts (Kousta et al., 2011).

Neither concreteness nor imageability can capture fine-grained ratings of sensorimotor words. Connell and Lynott (2012a) pointed out that even though auditory and gustatory feelings are part of our sensory experiences, auditory and gustatory concepts tended to be perceived as more abstract when the perceptual strength ratings were compared with concreteness ratings. Similarly, auditory and gustatory ratings did not coincide well with imageability ratings either—items with higher strength ratings in auditory and gustatory modalities were perceived as less imageable (Connell & Lynott, 2012a). In our own pilot studies, we found that a potential source of such unexpected and contradicting results may arise from the test instructions on concreteness and imageability. Definition based instructions could not differentiate the nuanced subtlety of the differences between these two concepts for lay persons. Example based instructions leave it to participants to make their own conceptual classifications without verification of consistency. These observations led to uncertainties of how to interpret results from experiments depending on these two constructs to capture the roles of embodied experiences in language comprehension.

In contrast, other recent studies found that perceptual strength is a stronger predictor than concreteness and imageability in interpreting lexical decision and word naming performance (Chedid et al., 2019; Connell & Lynott, 2012a, 2012b, 2014). Modality exclusivity studies of other languages also attested possible predictors for indexing lexical processing, including maximum perceptual strength (e.g. Connell & Lynott, 2012a, 2016a; Winter et al., 2018), summed perceptual strength (Filipović Đurđević et al., 2016), imageability ratings (Vergallito et al., 2020), and distance metrics at different exponent parameters (i.e. Minkowski 3 distance; Lynott et al., 2020). However, the best composite variable for predicting lexical processing behaviour still awaits attestation in Chinese. In addition, it is unclear which sensory modalities and action effectors are the key factors that affect lexical decision performance.

Since we are interested in exploring the predictive power of sensorimotor information in lexical processing as well as orthographic awareness in reading, we build our current work upon a lexical decision study (Tsang et al., 2018) and a concreteness study in Chinese (Xu & Li, 2020),[2] to explore the correlation between sensorimotor strength and semantic processing of word presentations. Following the embodied perspective, our two hypotheses on this correlation are:

[2]Only the concreteness dataset from Xu & Li (2020) was chosen because no comparable size of imageability test was available when the current study was conducted.

H2a: Sensorimotor composite variables provide better predictions in the lexical processing performance, e.g. reaction times (RTs) and accuracy, than other semantic variables (e.g. concreteness)

We notice that the role of specific sensorimotor dimensions in facilitating lexical decision tasks has not been addressed in previous studies, as only the predictive power of the sensorimotor composite variables was reported in the past literature. The second half of this hypothesis thus concerns the relations between specific sensory modality and action effector with the semantic processing performance. Similar to correlation to the concreteness effect, we hypothesize that:

H2b: More dominant sensory modalities and action effectors provide better predictions in the lexical processing performance, i.e. reaction times (RTs) and accuracy, than other less dominant modalities and/or effectors.

Method

Stimuli

In order to compare this study to the previous modality exclusivity study in Chinese (Chen et al., 2019) and to further integrate our results with concreteness ratings in Xu and Li (2020) and the lexical decision study in Mandarin Chinese (Tsang et al., 2018), we selected stimuli containing both the concrete and abstract concepts. For the concrete concepts, we ensure that our stimuli manifest all the five sensory modalities in a balanced way in our database. We paid special attention to ensure inclusion of adequate stimuli from the olfactory sense, which is found to contain limited lexical items in human languages (Levinson & Majid, 2014; Majid & Burenhult, 2014; San Roque et al., 2015; Zhao et al., 2019).

To serve the purpose mentioned above, the first batch of material in the current study contains nouns extracted from a Chinese online corpus, *Chinese Web 2011 (zhTenTen11)* in the *Sketch Engine* (Kilgarriff et al., 2014).[3] They were found as frequently co-occurring with perceptual verbs in perceptual events—看 *kàn* 'to look; to see,' 听 *tīng* 'to listen; to hear,' 尝 *cháng* 'to taste,' 闻 *wén* 'to smell,' 嗅 *xiù* 'to smell; to sniff,'[4] 摸 *mō* 'to touch,' and 感觉 *gǎnjué* 'to feel.'[5] This yielded a total of 757 lexical items across five sensory modalities and contained 515 pure nouns (only surfaced as nouns), 133 deverbal nouns (nouns that are derived from verbs), and 16 deadjectival nouns (originally adjectives but can also be used as nouns).

Next, the perceptual-related words were mapped to Xu & Li's (2020) concreteness ratings for two-character Chinese words and Tsang et al.'s (2018) word list in the lexical decision study. Xu & Li (2020) collected the concreteness ratings (on a scale from *1* = very concrete, *5* = very abstract) for two-character Chinese words that were retrieved from a Mega study of Lexical Decision in Simplified Chinese (MELD-SCH, Tsang et al., 2018). Whereas Tsang et al. (2018) reported a large dataset that contained lexical decision results, including various semantic variables such as mean reaction time (RT), mean standardised reaction time (zRT), mean error rate (ERR), word length in number of characters (length), total number of strokes (tstroke), and raw word frequency count based on SUBTLEX-CH (wfreq).[6] We used the two wordlists to look for intersections with our data because they were presented in simplified Chinese characters rather than traditional characters.[7] Note that even though no

[3] *Sketch Engine* is a platform that currently consists of 500 ready-to-use corpora in more than 90 languages. It offers tools and functions (e.g. word sketch, concordance, thesaurus, etc.) for users to analyse built-in as well as self-built corpora. *Chinese Web 2011 (zhTenTen11)* is a build-in and annotated corpus consisting of a total of 1.7 billion words and is made up of a web corpus which was collected in 2011 in mainland China. Accessed at https://the.sketchengine.co.uk/auth/corpora/.

[4] Two olfactory verbs were chosen because the instances related to olfactory perception are scarce in the corpus. This ensured that we extracted the largest possible number of results from the two different constructions in the corpus data.

[5] Although 感觉 *gǎnjué* 'to feel' is not considered a typical tactile verb, it is defined as "to perceive and distinguish external stimuli via bodily sensations" in the *Chinese WordNet 2.0* (Huang et al., 2010). Therefore, it is highly tactile-related and is believed to trigger bodily feelings, such as temperature-related sensations.

[6] SUBTLEX-CH contains word frequencies of Chinese based on film subtitles (Cai & Brysbaert, 2010).

[7] Simplified and traditional Chinese characters share the same origin in the writing system, albeit the former is adopted in mainland China (and some Chinese communities in Southeast Asia like Singapore and Malaysia), while the latter is mainly used in Taiwan, Hong Kong, and Macau. Over 2,200 Chinese characters were

effects of traditional characters were reported in the modality exclusivity norms in Chen et al. (2019), we would like to keep the inter-consistency by adopting the word lists that contain simplified word forms only.

332 sensory nouns were identified in the above-mentioned two wordlists and were tagged as "concrete" in the dataset ($M_{concreteness}$ = 2.24, $SD_{concreteness}$ = 0.64, $range_{concreteness}$ = 1.08 – 3.63). To compile a balanced word list containing both concrete and abstract nouns, we extracted another 332 disyllabic nouns in Xu & Li (2020) according to their ratings, ranked from high to low, and tagged as "abstract" ($M_{concreteness}$ = 3.88, $SD_{concreteness}$ = 0.18, $range_{concreteness}$ = 3.67 – 4.5). A Mann-Whitney test indicated that a statistically significant difference between the "concrete" group (mean rank = 167.50) and "abstract" group (mean rank = 499.50) exists: U ($N_{concrete}$ = 332, $N_{abstract}$ = 332) = .000, z = -22.299, p < .001). The word frequencies of the concrete and the abstract groups were controlled and balanced based on SUBTLEX-CH frequency count ($M_{concrete}$ = 658, $SD_{concrete}$ = 1667; $M_{abstract}$ = 946, $SD_{abstract}$ = 2865; p = 0.64). Thus, the stimuli used in this study contained 664 disyllabic nouns in Chinese, with concreteness ratings collected in Xu & Li (2020), and reaction time, error rates, number of strokes, word frequency, and other related dimensions provided in Tsang et al. (2018).

Procedure

This study mainly followed the design in the study of sensorimotor norms (Lynott et al., 2020). Participants were asked to rate how much they experience each concept (664 disyllabic nouns) based on their six perceptual senses (*vision, hearing, taste, smell, touch,* and *interoception*) and the five action effectors from different parts of the body (*foot/leg,*

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simplified and developed in the 1950s by the Chinese government to improve literacy rates in China (Honorof & Feldman, 2006; Yang & Wang, 2018). Most traditional and simplified characters are identical except for minor differences in their semantic radicals and the complexity of visual forms. For instance, the traditional character 話 *huà* 'speech; words' is simplified as 话, in which the left glyph 言 (7 strokes) is reduced to a simpler glyph 讠 (2 strokes); both radicals (言 and 讠) denote speech-related concepts.

hand/arm, *head excluding mouth*, *mouth/throat,* and *torso*), from *0* = no feelings at all, to *5* = very strong feelings. One thing to note is that "haptic" was used in Lynott et al. (2020) because they asked participants to rate concepts that could be "felt only by the hands;" however, Chen et al. (2019) did not specify feeling by hands but used the term 触觉 *chùjué* 'tactile experience' in general. We would like to consider both the haptic (i.e. seeking and obtaining information using one's hands) as well as the somaesthesia perceptions (i.e. skin senses related to pressure, temperature, and pain) in this study. Therefore, tactile (or touch) will be used in what follows. As a new sensation, interoception was translated as 身体内部感觉 *shēntǐ-nèibù-gǎnjué* 'bodily-internal-feelings' according to the term used in the psychological field.

The questionnaire was designed, distributed, and collected via an online survey platform Sojump (https://www.wjx.cn/) in Mainland China, with all the words written in Simplified Chinese. Demographic questions were asked at the beginning to collect the gender, age, highest education degree, language background, and residential place of the participants. Participants also needed to disclose cognitive disorders, i.e. impaired ability to perceive stimuli through sensory organs. Four simple Chinese knowledge questions, including transcribing pinyin to a word, identifying radical from a character, choosing the correct word composed of correct character forms, and selecting the correct semantic meaning for a word, were asked to ensure that the participants were able to comprehend basic Chinese. These questions were later used as the criteria to control the quality of the results.

Before the rating task started, we used instructions to provide examples for each dimension we asked. The instructions read:

*"**Visual sense** allows us to see this beautiful world; **hearing sense** permits us hearing all the sound; **gustatory sense** considers tastes; **olfactory sense** accounts for odours; **tactile sense** perceives temperature, pain, and textures of objects; **interoceptive sense***

*detects the feelings of hungry, exhausted, disgusting, etc. We also use our body parts to complete these perceptions. For example, we need to move our **head** or **torso** when we view the surroundings, we will open our **mouth** and articulate with our **throat** when we talk, we use our **hands (and arms)** to reach and grasp for objects, and we also resort to our **feet (and legs)** to walk or to kick. In what follows, you will see some nouns in Chinese. We would like you to judge how much you experience these concepts through each of the perceptions and actions we ask, on a scale from 0 = no feelings at all, to 5 = very strong feelings."* (translated)[8]

Participants

We recruited 600 participants from mainland China who use Mandarin Chinese and simplified Chinese characters in their daily life. The stimuli were randomly divided into 22 wordlists, with 30 words in each list. 20 participants saw each list of words. Each participant was rewarded with RMB10 Yuan (around USD $1.55) in exchange for participation. They spent an average of 15.7 mins on the survey.

In the data screening, apart from the quality control questions that required qualified participants to answer all four Chinese knowledge questions correctly, if a participant gave a low rating for a word that is clearly related to a particular sensory modality (<2), their answers were removed from the results. We used three words as the quality control words to eliminate unqualified answers, including 颜色 *yánsè* 'colour' (strongly related to visual sense), 音乐 *yīnyuè* 'music' (strongly related to auditory sense), and 味道 *wèidào* 'taste; smell' (strongly related to gustatory and olfactory senses). After eliminating all the problematic results, a total of 438 samples remained (female = 284; male = 154). The average age of participants was 26 years old (*SD* = 8.58, range = 18 – 60 years). All participants

[8]A sample of survey can be found at https://tinyurl.com/948x45rf.

claimed cities in mainland China as their current place of residence and said Chinese was their first language (inclusive of Chinese dialects).

Measurements

After the ratings were collected, we examined the sensorimotor norms by assigning the following measurements to each word:

- Perceptual and action strength: rating for the 11 dimensions (i.e. vision, hearing, taste, smell, touch, interoception, leg/foot, hand/arm, mouth/throat, head, and torso);
- Perceptual mean for the six sensory modalities: an average score of vision, hearing, taste, smell, touch, and interoception;
- Action mean for the five action effectors: an average score of leg/foot, hand/arm, mouth/throat, head, and torso;
- Dominant modality: the maximum perceptual strength across the six senses, which indicates the sensory modality that is most associated with that word;
- Dominant effector: the maximum action strength across the five effectors, which indicates the effector that is most associated with that word;
- Dominant sensorimotor: the maximum strength across the 11 sensorimotor dimensions, which indicates the sensorimotor dimension that is most associated with that word;
- Modality exclusivity: the extent to which the word is associated with a single perceptual modality, by calculating the range of mean strength ratings divided by their sum;
- Effector exclusivity: the extent to which the word is associated with a single action effector, by calculating the range of mean strength ratings divided by their sum;

- Sensorimotor exclusivity: the extent to which the word is associated with a single sensorimotor dimension by calculating the range of mean strength ratings divided by their sum.
- Maximum sensorimotor strength: the highest rating across the 11 sensorimotor dimensions for a concept.
- Summed sensorimotor strength: the sum of all the ratings across the 11 sensorimotor dimensions for a concept.
- Minkowski 3 distance: Minkowski distance at m = 3 of the vector from the origin. This represents all the 11 sensorimotor dimensions, with the influence of weaker dimensions attenuated.

Results

Descriptive sensorimotor strength

Overview of the sensorimotor strength

Inter-rater reliability was found highly reliable among the 11 dimensions, with Cronbach's Alpha α = .934 for visual, α = .940 for auditory, α = .939 for gustatory, α = .941 for olfactory, α = .931 for tactile, α = .954 for interoceptive, α = .968 for foot/let, α = .948 for hand/arm, α = .949 for mouth/throat, α = .957 for head, and α = .964 for torso. Table 1 indicates the overall mean ratings across the 11 sensorimotor dimensions, along with standard derivations and standard errors. They are further visualised in Figure 1. Figure 2 shows the 11 sensorimotor strengths for nine sample words.

[TABLE 1 ABOUT HERE]

[FIGURE 1 ABOUT HERE]

[FIGURE 2 ABOUT HERE]

Dominant sensorimotor dimensions and exclusivity

After the dominant perception and effector were assigned to the 664 concepts, the distribution of mean ratings and exclusivity percentage in each dominant sensorimotor were counted, as presented in Table 2. Some words share the same dominant sensorimotor dimension, so we categorised them in a new dimension, using the logogram "&" to indicate a shared dominance. For example, three words had their dominant sensory modality in both the gustatory and olfactory senses (i.e. both gustatory and olfactory received a score of 4.67), so that they were categorised as "Gustatory & Olfactory."

[TABLE 2 ABOUT HERE]

Table 2 shows that interoception is the dominant sense among the sensory modalities (n = 289; 43.5%), followed by visual (n = 211; 31.8%), auditory (n = 122; 18.4%), gustatory (n = 19; 2.9%), olfactory, and tactile (n = 8; 1.2%). Four words had their dominance in visual and interoception (n = 4; 0.6%), and three words shared the dominant modality in gustatory and olfactory (n = 3; 0.5%). If the new dimension, interoception, is excluded, the other five traditional senses generally follow the tendency seen in previous modality exclusivity studies: visual sense is perceived as being associated with most of the concepts, far outweighing the other dominant modalities; while gustatory and olfactory senses shared roughly the last two places, having the lowest number of ratings as the dominant sense (Lynott & Connell, 2009, 2013; Lynott et al., 2020; Miklashevsky, 2018; Vergallito et al., 2020). An unexpected finding is the leading position of interoception and it is even more dominant than the visual sense. The reason for this may be that interoception dominates abstract concepts (Zhong et al., 2021), and abstract concepts account for half of the stimuli in our dataset. Therefore, participants tended to give those that could not be perceived by any of the five senses a higher rating in interoception. Note that interoception is also relatively dominant in Lynott et al. (2020)—it took third place among the six perceptions, right after the visual and auditory senses.

The modality exclusivity scores ranged from the lowest 3.6% (i.e. 刺激 *cìjī* ‘irritation’) to the highest 51.9% (i.e. 假设 *jiǎshè* ‘assumption’). The auditory modality received the highest modality exclusivity score (30.1%; more unimodal), and gustatory sense received the lowest score (14.5%; more multimodal) of all the senses. In general, the modality exclusivity scores are considered low (below 35%) (Lynott & Connell, 2009). The exclusivity scores statistically differed across dominant modalities: $F(7, 656) = 12.9$, $p < .001$, $\eta^2p = .121$. Post hoc comparisons with Bonferroni corrections indicated that auditory dominance scored significantly higher in modality exclusivity than those for gustatory and interoceptive ($p < .001$), visual ($p < .05$), but not for tactile ($p = .267$) and olfactory ($p = .702$). On the contrary, gustatory dominance received a significantly lower score in exclusivity than visual and interoceptive ($p < .001$).

As nouns mostly represent objects and entities, action strength is undoubtedly low for these concepts. Noun concepts are primarily associated with head excluding mouth and throat (*n* = 205; 30.9%), followed by mouth and throat (*n* = 198; 29.8%), hand and arm (*n* = 140; 21.1%), torso (*n* = 49; 7.4%), and leg and foot (*n* = 36; 5.4%). The dominant tendency among action effectors in this study generally follows that in Lynott et al. (2020): head is the most dominant action effector (67%), whereas foot and leg (4%) and torso (2%) are the least two. One interesting fact is that the number of mouth and throat as the dominant effector is much higher in Chinese than in English (29.8% vs 9%). Another noticeable observation is that almost all the action effectors jointly shared a dominant place with other effectors. Among which, hand and arm, head, and torso are the body parts that share the most dominant action effector with others, i.e. they have associations with all the other effectors. Such close interrelationships among action effectors render effector exclusivity extremely low (ranging from 2.7% for the mouth/throat & torso dominance to 16.5% for the mouth/throat dominance). The mouth/throat dominance is the most unimodal (16.5%), followed by hand/arm (12.8%), head (11.9%), leg/foot (10.9%), and torso (9.3%). However, the effector exclusivity for the dominant action effectors did not exhibit much difference: $F(14, 649) = 1.63$, $p = .066$, $\eta^2p = .034$.

When observing the 11 sensorimotor dimensions as a whole, the maximum strength for all the concepts was found predominantly in the six perceptual modalities rather than their action effectors counterparts. It is also reflected in the deviation in the perceptual mean (2.04) and the action mean (1.78): the perceptual mean (*median* = 1.98) is significantly higher than the action mean (*median* = 1.71): $T = 176875$, $z = -13.641$, $p = 0.000$, using a Wilcoxon signed-rank test. Therefore, the dominant sensorimotor dimensions and the sensorimotor exclusivity are almost identical to the dominant sensory modalities and modality exclusivity scores. Six words previously dominated by visual and auditory perceptions have changed their dominances to leg/foot ($n = 4$; 0.6%) and hand/arm ($n = 2$; 0.3%). Moreover, the action strength of the mouth/throat was either replaced by or shared the leading position with auditory and gustatory senses in four concepts.

Correlations among sensorimotor dimensions

Figure 3 plots a correlation across the 11 sensorimotor dimensions.

[FIGURE 3 ABOUT HERE]

Among the perceptual modalities, gustatory and olfactory displayed an appreciably strong association with each other, as did the visual and tactile senses, which is in line with all the previous norming studies (e.g. Chen et al., 2019; Lynott et al., 2020; Vergallito et al., 2020). This finding confirms that regardless of the composition or language of the dataset, the correlations between these two pairs of senses, i.e. gustatory-olfactory and visual-tactile, are robust. Olfactory-tactile and gustatory-tactile also showed relatively strong positive correlations, reflecting that apart from explicit gustatory-olfactory relationships in food-related items, the tactile sense is also relevant in the perception of the temperature and texture of food (cf. Zhong & Huang, 2020; Zhong et al., 2021). Other positive but weaker relationships existed between visual-auditory, visual-gustatory, and visual-olfactory, suggesting that visual perception dominates most physical substances. The only negative correlation found for visual sense is with interoception, and in fact, interoceptive strength was also negatively correlated to tactile sense but positively related to auditory, gustatory, and olfactory perceptions. This finding is consistent with Connell et al. (2018), implying that concepts that can be perceived inside our body tend not to be visible or touchable but can sometimes be heard, tasted, or smelled, although none of the relationships are particularly strong. Auditory modality demonstrated its uniqueness by showing negative correlations with other sensory modalities, especially with the gustatory, olfactory, and tactile senses. The only exception existed in the visual-auditory correlation since some auditory-dominant items could also be visualised (e.g. 故事 *gùshì* ‘story,’ 演讲 *yǎnjiǎng* ‘speech,’ and 耳机 *ěrjī* ‘earphone’).

All five action effectors presented positive correlations with each other, although the degree of strength varied. Similar to the results in Lynott et al. (2020), the strength of the torso saw the most robust relation with leg and foot, followed by hand and arm, head, and finally mouth and throat. The intertwined interrelationship between the torso and other effectors is mainly because all the body parts evenly participate in performing actions in noun concepts. For example, the word 足球 *zúqiú* ‘football’ undoubtedly received the highest strength in leg and foot (4.79), because one only uses feet to kick the ball. However, torso (3.94) and hand and arm (3.16) are equally crucial in playing football because one needs to move his/her body and swing his/her arms to balance the body when running. Finally, head

(2.95) and even mouth/throat (1.68) are also used when playing football or watching football games—for example, to cheer for the team that one supports.

Thus, we suggest that noun concepts exploit action effectors differently than those for verb concepts: the correlation strength may depend on the semantic network that the concept represents in people's mental lexicon. For example, a football can be kicked (using leg and foot, torso, hand and arm, and head), and a football (game) can be watched (the head is required, throat and mouth are also needed to express one's feelings). Action effectors may evenly take part in noun concepts on this ground, and they cannot be separable to a certain degree. In contrast, verb concepts, which mostly reflect actions and events, are represented by sole effectors and thus reject body parts that are not involved in particular actions (e.g. mouth/throat might not be exploited in the verb concept of *kick*). This highly intertwined relationship among all the body parts in the semantic representations of noun concepts also explains the extremely low exclusivity of action effectors in nouns.

For that reason, action effectors also were positively correlated with most sensory modalities. Visual and tactile perceptions had the closest relationship to hand and arm, and the least close with mouth and throat; auditory was strongly correlated with mouth and throat while the least correlated with hand and arm; gustatory and olfactory ere strongly correlated with mouth and throat as well. The action effectors overall had much weaker correlations with interoception than those with the other five sensory modalities. The only negative interaction was found between hand/arm and interoception, and the reason for this might be because hand actions are mostly engaged in perceiving tangible and touchable objects. Therefore, the concepts that received high ratings in hand/arm strength tended to exclude those that could not be touched. This is also the reason why interoception is negatively correlated to the tactile sense.

Orthographic representations via sensorimotor strength

To identify potential correlations between orthography with semantic ORL and sensorimotor strength, we analysed the distribution of the four-character types and their relations with the dominant sensorimotor dimensions. Note that the data in this study contains two-syllable words, which means each word shall have two radicals and two-character types (either different or the same). Therefore, we calculate the character type for the first character and the second character in each dominant sensorimotor dimension, and report them as a whole. For instance, as shown in Table 3, there are 37 pictographs for character 1 and 33 for character 2, so the number reported for pictographs in the visual dominant modality is 70, and the mean rank is for both characters 1 and 2.

[TABLE 3 ABOUT HERE]

Among the four-character types, phono-semantics are undoubtedly the most predominant in all the modalities in Chinese characters. Ideographs were not found for gustatory, olfactory, and tactile dominant senses—the main reason is probably because the three modalities have the least number in dominance. We further tested the differences of mean ranks of character types across dominant modalities. The Kruskal-Wallis H test showed that no statistically significant differences were found, visual: χ^2 (3) = 5.466, p = .141, auditory: χ^2 (3) = 1.516, p = .679, gustatory: χ^2 (2) = 0.474, p = .789, olfactory: χ^2 (2) = 5.136, p = .077, tactile: χ^2 (2) = 0.479, p = .787, interoceptive: χ^2 (3) = 4.108, p = .250.

The same method was applied to dominant effectors, as shown in Table 4. All the four-character types were identified among the five effectors. Interestingly, statistically significant differences were exhibited for character types mouth/throat (χ^2 (3) = 8.873, p = < .05) and head (χ^2 (3) = 15.398, p = < .05) as the dominant effectors, character types. In contrast, no such differences were shown for leg/foot: χ^2 (3) = 0.329, p = .954, hand/arm: χ^2 (3) = 1.386, p = .709, and torso: χ^2 (3) = 1.122, p = .772. In particular, the mean rank for ideographic compounds is statistically lower than of the phono-semantic types in the dominant effectors mouth/throat and head. We hypothesize this is because the mouth/throat is the main articulator of sound, thus containing a more apparent affiliation with the phonetic information.

[TABLE 4 ABOUT HERE]

Apart from character types, radicals are considered a fundamental component of Chinese characters. As mentioned previously, Chinese radicals can hold information about the meaning of the character and signify connections between semantic meanings and their dominant perceptual modalities and action effectors. In Table 5, we summarised the number of radicals (N) in the first and second character for each sensorimotor dimension and organised them according to the maximum strength (MS) that the dimension received.[9]

[TABLE 5 ABOUT HERE]

It is observed that each perceptual or action strength would have its ‘preferred’ radicals, and most of the time, the semantic meaning of that radical will favour that particular dimension in terms of its maximum strength. The visual modality mainly selects the radicals that could be visualised and represented as a concrete object in the world, including *sun, hole, fire, wind, grass*, and *colour*. The auditory modality is more related to radicals that can produce sounds, like *mouth, drum*, *person, insect*, or is directly indicated by *saying* and *yawning*. Gustatory and olfactory modalities share most of the radicals that denote food—*sheep, insect, rice*, or relate to tools used to make or eat food—*fire, mouth*, or indicate places that can grow food—*grass, rice paddy*. Words receiving high ratings in tactile modality mostly contain radicals of body parts with tactile senses (e.g. *hand, flesh*) or can be ‘in touch with’ intangible concepts (e.g. *heart*). Interoceptive perception is found to be mostly pertinent to internal feelings—*heart*, *power*, *sickness*, and *person*. Turning to action strength, they

[9] Note that only the top 5 radicals were presented because of the page limit.

were likewise represented by those highly relevant radicals to a large extent. For example, *foot, flesh, power, stop* predict high strength in foot and leg; *hand* is selected by hand and arm; radicals implying *food, eat, mouth, speech,* and *yawn* are primarily associated with mouth and throat; *flesh, head, power, hair, and speech* are found for the head; and, torso connects *foot, body, bone*, and *person*.

Prediction of word processing performance via sensorimotor strength

Bayesian linear regression was conducted following Lynott et al. (2020). The lexical decision data was retrieved from MELD-SCH (Tsang et al., 2018), with the focus of two dependent variables—standardised reaction times with individual variance removed (zRT) and error rates (ERR). Other lexical characteristics, including word length in the number of characters, the total number of strokes, word frequency, and contextual diversity based on SUBTLEX-CH (Cai & Brysbaert, 2010), were extracted as lexical predictors. These predictors were introduced to build a null hypothesis model, and then a composite variable was added to form an alternative model. Bayes factors (BF)[10] was then used to quantify the evidence in favour of the alternative model over the null hypothesis model. We repeat the same procedure to identify the best-performing composite variable for predicting zRT and ERR of the current dataset based on four candidate models, including concreteness, maximum sensorimotor strength, summed sensorimotor strength, and Minkowski 3 sensorimotor strength. In addition to the null hypothesis model, the four models for predicting the two dependent variables are sorted according to BF, as can be seen in Table 6.

[TABLE 6 ABOUT HERE]

Overall, we found that all composite variables of the sensorimotor norms reliably predicted lexical decision performance above and beyond the null hypothesis of lexical

[10]The Bayes factor is the ratio of the likelihood probability of two competing hypotheses (usually null and alternative hypothesis) and it helps us to quantify the support of one model over another.

predictors for response times and accuracy. It is noted that lexical reaction time is mainly related to the maximum sensorimotor strength, while the error rates are mostly predictable by summed sensorimotor strength.[11] The result differs from that of Lynott et al. (2020), where they demonstrated the equal weight of the 11 dimensions of sensorimotor strength for the semantic interpretation of words. We found instead that maximum sensorimotor strength and summed sensorimotor strength were the most powerful semantic facilitators in lexical decision performance.

The questions of which dimension(s) play more salient roles and to what degrees have not been answered in the existing literature. Therefore, we look further into the specific perceptual and action variables in terms of their predicting power for the lexical processing task. We modelled on the six sensory modalities and five action effectors with Bayesian linear regression and visualised their predicting power with the image plotting function based on the log posterior odds (provided by the *BAS* package), as shown in Figures 4 and 5.

[FIGURE 4 ABOUT HERE]

[FIGURE 5 ABOUT HERE]

In the two plots, each row corresponds to each variable included in the full model and one extra row for the intercept. In each column, we can see all possible models (2^{11} because we have 11 variables included) sorted by their posterior probability from the best to worst rank on the top (from left to right). From the images above, we can see that the best five predictors of sensorimotor strength for zRT are visual, auditory, tactile, interoceptive, and mouth/throat; whereas the best five predictors of sensorimotor strength for ERR are visual, auditory, interoceptive, mouth/throat, and head. The result shows that visual, auditory,

[11]But note that all the sensorimotor composite variables performed relatively weak in predicting error rates, as suggested by the consistent low BFs across models. Therefore, the result where we found the maximum sensorimotor strength as the strongest predictor for reaction times in the lexical decision performance is more reliable.

interoceptive, and mouth/throat are among the most salient factors for predicting both the zRT and ERR.

Additional analysis: orthographic effects on the word processing performance via sensorimotor strength

To understand the salience of the four predictors for lexical decision, we assume an orthographic effect of the Chinese characters upon people's semantic processing and comprehension. Hence, we propose to discuss the relation of the orthographical influence and the lexical processing task via sensorimotor factors. Table 7 summarises the distribution of all the orthographic types of the 664 two-character words with examples.

[TABLE 7 ABOUT HERE]

As shown in Table 7, the top three orthography types are: phono-semantic-phono-semantic (PP), compound_ideograph-phono-semantic (CP), and phono-semantic-compound_ideograph (PC). Considering the powerful effect of the models, the sample size of the target groups was taken into account to focus on the top three types, as highlighted in bold, and conduct subset Bayesian linear regressions. Results are displayed in Table 8.

[TABLE 8 ABOUT HERE]

From Table 8, we can observe the marginal posterior inclusion probabilities for each of the covariates, with marginal posterior inclusion probabilities that are highest for the perceptual and action variables in bold (i.e. important variables for explaining the data and prediction). The results show that the reaction times and accuracy of lexical decision performance in PP type have a solid connection to the auditory, mouth/throat, and head; whereas the two lexical decision dimensions in CP are more pertinent to visual and mouth/throat, and rely more on visual and hand/arm in PC. Overall, the visual, auditory, and mouth/throat variables are prominent predictors among the top three orthographic types, which verifies our assumption of radical effect to lexical processing.

Discussion

We collected the sensorimotor ratings for Chinese disyllabic compounds to better understand the correlation between sensorimotor strength and orthographic representations and semantic processing performance. After demonstrating the results of descriptive sensorimotor strength (including dominant sensorimotor dimensions, modality exclusivity, and correlations among sensorimotor dimensions), orthographic representations via sensorimotor strength, and prediction of word processing performance via sensorimotor strength, in what follows, we address the two main research questions in this paper: to what extent can sensorimotor strength 1) reflect orthographic representations, and 2) predict word processing behaviour.

Orthographic representations and sensorimotor strength

We found evidence in this study to support the first hypothesis: semantic radicals can serve as an orthographic signal of the dominant sensorimotor dimensions (H1a). The results showed that each semantical radical is reflected in its corresponding dominant sensorimotor dimension. The dominant visual modality mainly selects radicals that can be visualised as a concrete object; the auditory modality is more related to the radicals that can produce and perceive sounds; gustatory and olfactory modalities share most of the radicals that denote food intake; words that received strong strength in tactile modality mostly contain body parts that are used to touch and feel objects; and interoceptive perception is found mostly pertinent to internal feelings. Similar findings were suggested for action effectors, in which strong strength in foot/leg, hand/arm, mouth/throat, head, and torso is reflected in their respective semantic radicals.

Mixed results were found for the second hypothesis, i.e. formation types can serve as an orthographic signal for the dominant sensorimotor dimension (*H1b*), suggesting that phonological associations with sensorimotor strength are slightly weaker as compared to semantic radicals. In contrast to the finding of the phono-semantic effects on auditory strength in monosyllabic adjectives in Chinese (Chen et al., 2019), the direct orthographic effects on modality strength are not salient in our study. One possible reason is that the two characters and two-or-more-concept-denoting components in each disyllabic compound masked the transparency of the orthographic types. Note that there were 16 types of combinations of orthographic structures in the dataset, as seen in Table 7. However, interestingly, a correlation between some radicals and action strength, including mouth/throat and head, was observed in this study. Possibly, this is because mouth/throat and head are the two dominant action effectors, and they are also the two primary effectors that initiate actions and produce sounds. This result is further confirmed by the effects of orthographic types in predicting lexical decision performance via sensorimotor strength. The action effectors (e.g. mouth/throat and head) bolstered response speed and accuracy of the decision in the combination of phono-semantic structures, i.e. two semantic radicals and two phonetic symbols.

In addition, auditory strength is also found to facilitate the lexical processing performance in the combination of phono-semantic structures. However, when the phonetic cues are weakened in other types—CP and PC—the sensorimotor predictors shift to other more visual-related dimensions, such as visual and hand/arm. It is also interesting to note that since most Chinese phonetic compounds hold a left-right structure (Hsiao & Shillcock, 2006), i.e. the semantic radical on the left and the phonetic symbol on the right (like CP), the lexical decision performance of CP is still somewhat related to mouth/throat. However, the phonological-related dimensions in reaction times and the accuracy for PC (a left phonetic symbol and a right semantic radical) are much weaker. The results are in line with the importance of phonetic symbols in word recognition studies, in which phonological codes were found to facilitate identification of the Chinese characters to a similar degree as their semantic counterparts (e.g. Perfetti & Zhang, 1991; Zhou & Marslen-Wilson, 1999), and the regular phonetic compounds (i.e. those sharing the identical syllables with their corresponding phonetic symbols) will elicit higher accuracy and faster reaction times than irregular phonetic compound recognition (Lau & Ma, 2018; Law et al., 2005).

In sum, as a crucial orthographic unit in Chinese characters, the function of semantic radicals is evidenced by the sensorimotor strength of compounds containing them—the maximum strength of the sensorimotor dimension displayed an intertwined relationship with the radicals that denote semantic meaning(s) of that sensorimotor vector. We found that phonological associations were not as significantly correlated to auditory strength at the compound level in general as those found in Chen et al. (2019) at the character level. Such an effect does show up when action effectors directly engaged in auditory production (i.e. mouth/throat and head) are involved. They are found to be significantly higher in their strength in phono-semantic types than in other formation types signalling visual cues only. Moreover, the additional analysis of the orthographic effects in the word processing performance via sensorimotor strength verified our assumption that auditory, mouth/throat, and head strength could predict the lexical processing performance in the phono-semantic types because all three of these sensorimotor dimensions are phonologically associated; while visual and hand/arm strength will facilitate the speed and accuracy in other character types that mostly contain visual cues.

Semantic processing and sensorimotor strength

The use of sensorimotor strength to predict word processing performance conformed to our hypotheses. For the first hypothesis, sensorimotor composite variables provide better predictions in the lexical processing performance, e.g. reaction times (RTs) and accuracy, than other semantic variables (e.g. concreteness). For (*H2a*) we found that, as hypothesized, maximum sensorimotor strength is the most powerful semantic facilitator in the latencies in lexical processing while summed sensorimotor strength best explains error rates. Across all candidate variables, concreteness is the least powerful predictor to explain reaction times and/or error rates. Although Minkowski 3 sensorimotor strength was not the most powerful predictor in predicting word processing performance in our study, it still appeared to be the second predictor for both the reaction times and error rates. Given that maximum and summed perceptual strengths are two powerful semantic facilitators in word recognition tasks (e.g. Connell & Lynott, 2012a, 2016a; Filipović Đurđević et al., 2016; Winter et al., 2018), our results are consistent with previous studies. In general, despite variations in composite data and language differences across studies that might suggest heterogenous results (cf. Vergallito et al., 2020), the critical role that sensorimotor strength and sensorimotor dimensions play in visual word recognition tasks need to be valued.

Additionally, the present study suggests individual sensorimotor dimension as the predictor for the lexical decision reaction times and accuracy. The overlapping best predictors for reaction times and error rates include visual, auditory, interoceptive, and mouth/throat. This result coincides with our second hypothesis: more dominant sensory modalities and action effectors provide better predictions in the lexical processing performance, i.e. reaction times (RTs) and accuracy, than other less dominant modalities and/or effectors (*H2b*). All four sensorimotor dimensions are the most dominant in terms of their strength—especially the consistently outstanding performance of the visual sense (Lynott & Connell, 2013; Speed & Majid, 2017). The overarching position of the visual sense among the sensorimotor dimensions, together with its robust performance in predicting latencies, is supported by its dominance in human perceptual systems as the visual sensation takes up the largest region in the brain (Drury et al., 1996).

In addition, some studies also proposed a relation between more valenced (emotion-laded) words with reaction times (Kousta et al., 2011; Kousta et al., 2009; Kuperman et al., 2014). This may be related to the fact that the Chinese language sees a particular connection with physical and mental feelings via interoception. For instance, words with interoception as their dominant modality mostly embrace internal organs such as 心 *xīn* ‘heart,’ 胸 *xiōng* ‘chest,’ and 胆 *dǎn* ‘gall,’ as well as carry the semantic radicals like *heart*, *power* and *strength*, and *sickness*. Such association is because the Chinese language primarily resorts to internal body organs to conceptualise emotion-related metaphors (Yu, 2008, 2009). However, this proposal awaits further attestation since the emotion/valence vector is not considered in the current study.

Conclusion

Disyllabic words are the most dominant word types in modern Chinese (Huang et al., 2002). This study presents the first, most comprehensive sensorimotor norms for Chinese disyllabic nouns. With modality-(and action-)specific information examined in the noun concepts in Chinese, we demonstrated interoception and vision as the two dominant sensory modalities that primarily account for abstract and concrete concepts, respectively; in addition, head (excluding mouth and throat) and mouth/throat were the two dominant action effectors.

In spite of subtle differences in the tendencies of modality exclusivity and correlations among sensory modalities compared to previous studies, several generalisations have been affirmed across languages and among different compositions of datasets. For example, the visual modality is the most dominant and olfactory is the least dominant sense. Moreover, visual and auditory are the two most unimodal senses, and the gustatory sense is the most multimodal cross-linguistically.

In addition, the most robust sensory modality correlations are seen in gustatory-olfactory and visual-haptic, whereas the negative relationship between the auditory modality and the other senses seemed to be a consistent pattern except for Chinese adjectives, where the auditory sense was positively correlated to the gustatory, olfactory, and tactile senses (Chen et al., 2019; see also Zhao et al., 2019). The reason might be the cross-modal nature of

Chinese sensory adjectives used in Chen et al. (2019) since the auditory sense is usually considered the “target domain” in the directionality of linguistic synesthesia. Most adjectives that describe auditory concepts can also be used to describe other senses; for example, sweet[taste] and sharp[tactile] both modify the word voice[hearing] (cf. Strik Lievers, 2015; Williams, 1976; Zhao et al., 2019).[12] The nature of grammatical categorisation composite also partly explains the low modality exclusivity and action effectors exclusivity in this study because, for example, noun concepts are multimodal in nature and do not elicit much action compared to verbs.

Apart from presenting the sensorimotor norms of Chinese disyllabic nouns in this paper, we grounded our discussion of the intersection of sensorimotor strength and orthographic representations in the framework of embodied cognition. Specifically, semantic radicals signal a connection between orthographic representations and their dominant sensorimotor dimensions, whereas phono-semantic compounds are closely related to action effectors that directly produce sounds, e.g. mouth/throat and head. Moreover, sensorimotor composite variables successfully predicted word processing performance in this study. We also further attested the “embodied semantics effects” (Connell & Lynott, 2016b) by proposing that the more dominant the sensorimotor dimension is, the faster and more accurate the performance will be expected to be in word recognition tasks. Overall, the current study demonstrates language-universal as well as language-specific cognitive processing of the sensorimotor system by corroborating that embodied cognition may ground sensory-motor features of semantic representations of concepts.

The current study sheds light on the issue of whether phonological or orthographic awareness is involved in reading in Mandarin Chinese. Although phonological awareness has

[12]In linguistic synesthesia studies meaning transfers from one sensory modality to other sensory domains; and synesthetic words are commonly realised in the form of adjectives.

been attested as part of the development of the cognitive skill reading in many languages, studies on Mandarin Chinese have reported mixed results. Noting Chinese's unique feature of having semantics, instead of phonology, as ORL, Lee and Huang (2022) provided several facts and linguistic generalisations to argue that what has been widely reported as phonological awareness should, in fact, be orthographic awareness. In addition to showing many Chinese phonological rules that are constrained by orthographic conditions, they also cited a number of recent studies showing that phonological awareness in young Mandarin speakers is highly correlated to their acquisition of phonological writing systems (either Pinyin romanisation or the Bo-Po-Mo-Fo national alphabets, e.g. Lin et al., 2020). In addition, they also argued that all previous studies on phonological awareness only showed awareness of phonological generalisations that are also orthographically encoded. Our current study confirms that the predictive power of orthographically encoded sensorimotor information underlines the awareness of such information when reading. One simple and intuitive hypothesis that could account for the results found our current study (and for the consistent phonological awareness results in multiple languages as well as the inconsistent phonological awareness results in Mandarin), is that reading involves the awareness of the orthographic encoding of linguistic information in all languages and all language writing systems. In other words, the kind of linguistic knowledge that speakers gain awareness of depends on the kind of information encoded in the acquired orthography. This suggests that *a priori* awareness of a particular linguistic module (say phonology) does not take precedence over awareness of another module. The overwhelming evidence of phonological awareness from many languages is simply the logical consequence of orthographic awareness, and it is because phonology is the ORL in their orthography (for both writing and reading). The uniqueness of having a writing system with semantics as the ORL in Chinese not only allows us to explore the interaction of sensorimotor dimensions with rich lexical cues but also to underline the critical role of orthographic awareness in language processing.

Furthermore, with the attested intersection of sensorimotor strength, orthographic representation, and semantic processing in Chinese, this study provides a sensorimotor-specific database for future exploration of the neural networks underlying different levels of language processing. The three linguistic levels that are lexically represented, i.e. orthography, phonology, and semantics, demonstrate convergent as well as divergent activations in cortical regions when processing Chinese characters (e.g., Booth et al., 2006; Siok et al., 2020; Tan et al., 2005; Wu et al., 2012). A number of functional magnetic resonance imaging (fMRI) studies have shown that the left middle frontal gyrus is consistently activated in orthographic processing, which is the area serving for visuospatial information analyses (e.g., Wu et al., 2012). Phonological processing, although sharing convergent areas with orthographical processing, additionally recruits the right superior temporal gyrus that deals with tonal representations of Chinese characters (Tan et al., 2001) and intonation perception in speech prosody (Zhang et al., 2010). With regard to semantic processing, the additional activated cortical regions such as the left middle temporal gyrus and the anterior ventral part of the left inferior frontal gyrus (Wu et al., 2012) were suggested responsible for verbal semantic representations (Booth et al., 2002; Booth et al., 2006). Furthermore, a convergence of sensorimotor inputs and their semantic representations in functional brain activations was tapped by functional activation maps in Neurosynth (Yarkoni et al., 2011)[13] and English sensorimotor norms (Lynott et al., 2020) in Reilly et al. (2020). Their findings unravelled a "near-perfect correlation" between the functional voxel counts and sensorimotor ratings of the English lexicon. Specifically, a sensory hierarchy dominated

[13] Neurosynth is a platform containing a large-scale and automated synthesis of fMRI data. Accessed at https://neurosynth.org/.

by vision and hearing and underrepresented by taste and smell is likewise reflected by their corresponding functional activation patterns in the human brain (Reilly et al., 2020). Given the uniqueness of the Chinese writing system, with semantics as the ORL, the sensorimotor database of the Chinese language will provide unique opportunities for testing several issues that cannot be teased apart based on previously available data from languages with phonology as the ORL in their writing systems. A critical and challenging issue is the conceptualisation and processing of different types of embodiment. A sensorimotor concept can be embodied through actual bodily experience (i.e. sensation or motion), individuated and visualised as the location of sensation (i.e. the faculty/organ that has the function or enacts the sensorimotor events) as well as the undergoing of sensorimotor events. The last is instantiated by activating audial knowledge when reading radical-phonetic compound characters.

Several limitations are noted in the current work. First, for the convenience of taking sensorimotor strength into account for exploring word processing performance, we selected stimuli consisting of half concrete and half abstract concepts. This might lead to bias in stimuli selection. The only surveyed lexical category in this study, noun concepts, might also not reflect the full picture of conceptual processing. Moreover, because of the availability constraints, we are not able to take other important semantic variables into consideration when predicting word processing performance, such as imageability, age of acquisition (AOA), and valence and arousal effects. Thus, more research should be devoted to developing extensive databases of sensorimotor norms and psycholinguistic variables in a variety of languages. Future work is also recommended to consider morphological structures and the headedness effect since semantic transparency may play a role in predicting meanings of disyllabic compounds in Chinese (Wang et al., 2019). Furthermore, with the norm of the complex system of the sensorimotor as well as the complex system of the phonological neighbourhood (Neergaard et al., 2021), we can explore if, and, how the lexical meaning and sound systems might interact with each other in our language.

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Disclosure statement

The authors declare that there is no conflict of interest.

Ethics approval

This study was conducted following the Human Subjects Ethics Sub-committee (HSESC) (or its Delegate) of The Hong Kong Polytechnic University (HSESC Reference Number: HSEARS20200810001).

Availability of data and materials

All the data and materials in this study are available at our OSF page https://tinyurl.com/948x45rf.

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