

The Effect of Referential and Emotional Information on Novel Word Learning: A fNIRS Study

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Abstract—Language learning focuses on word learning, especially the word learning combined with context. The referential and emotional information in the context could affect the novel word learning. However, there is little research on the effect of referential and emotional information on novel word learning and its neural mechanisms. The current study used functional near-infrared spectroscopy (fNIRS) techniques to examine the neural mechanisms underlying the effect of referential and emotional information on novel word learning. After learning the meaning of novel words in different sentences, participants were instructed to complete a semantic consistency judgement task and a source judgement task. The results showed that: (1) the referential information affected the novel word learning, indicating that the self-referential information could promote the novel word learning; (2) the referential and emotional information jointly affected the novel word learning, manifesting the significant interaction between referential and emotional information; (3) these effects were associated with neural activities in the frontal and temporal lobe, mainly in the activation of the dorsolateral prefrontal cortex (DLPFC), the inferior frontal gyrus (IFG), the middle temporal gyrus (MTG), the superior temporal gyrus (STG), and the pre-motor and supplementary motor cortex. These results revealed the integrative contributions of both referential and emotional information to novel word learning.

Key words: referential information, emotional information, novel word learning, fNIRS

INTRODUCTION

Language is an important medium for human beings to explore the external world, carry out thinking activities, transmit thoughts and emotions. The importance of learning languages has become more and more prominent. Language learning focuses on word learning, especially the word learning combined with context, which can provide learners with more effective learning clues and promote learners' understanding of word [1]. Especially for comprehending novel words, learners integrate novel words with specific contexts to deduce the meaning of novel words [2].

Referential information has a vital influence on word learning, playing an important role in memory formation, organization, and retrieval [3]. Research have revealed that individuals exhibit faster and more accurate processing of self-referential information, and have a better memory effect, when compared to non-self-referential information, which is called the “self-reference effect” (SRE) [4]. Zhou et al. [5] asked participants to use personal pronouns (“my”, “his”) to form sentences with different daily objects. The findings demonstrated that the memory of items related to the self was notably better when compared with those related to others. Turk et al. [6] found that compared with other-referential conditions, participants were able to construct lengthier sentences, and their spelling accuracy exhibited an increase of over 20% in the self-referential condition. Additionally, some brain imaging studies found that stimuli related to self-reference primarily activated the prefrontal cortex (PFC), particularly the medial prefrontal cortex and the inferior frontal gyrus (IFG) [7; 8].

Emotional information is also an important factor affecting word comprehension [9]. Beaucousin et al. [10] found that compared with neutral sentences, participants processed emotional sentences faster and had a higher correct comprehension rate. Maratos et al. [11] asked participants to learn neutral words presented in different valences sentences, and fMRI was utilized to assess brain activation during the test stage. The results showed that in negative contexts, word recognition activated the right dorsolateral prefrontal cortex (DLPFC), the posterior cingulate cortex, the left amygdala, the hippocampus and the right lingual gyrus to a greater extent. In positive contexts, word recognition activated the bilateral prefrontal and orbitofrontal lobes, as well as the left anterior temporal cortex, to a greater extent. Guo et al. [12] asked participants to learn novel words after being elicited different emotions by emotional pictures and then respectively make judgements

about the semantic category and semantic consistency of the words. The results show that negative emotional states hinder the novel word learning. Another study [9] found that the performance of word learning in negative contexts is poorer than that in neutral and positive contexts. The activation degree of word learning in the anterior cingulate cortex, bilateral insula, and left IFG was modulated by the emotionality of context through the fMRI scanning.

About the role of referential and emotional information in word learning, D'Argembeau et al. [13] have found that there is no interaction in the recognition memory task. In the free recall task, positive self-referential adjectives had a better memory effect than negative self-referential adjectives, and there was no significant difference in the memory effect of either positive or negative adjectives under other-reference, indicating that they acted independently in the coding stage, and acted together in the extraction stage. Fossati et al. [14] found that no matter the words were positive or negative, the right dorsomedial PFC would be activated under self-reference conditions. This suggests that referential information and emotional information may act independently of each other. However, Watson et al. [15] found that participants respond faster to positive self-related words and negative other-related words, and the evoked N400 amplitude is larger. This indicates that referential and emotional information jointly affect word processing, and there is "a self-positivity bias". Thus, how do referential and emotional information influence the novel word learning? Do they interact or operate independently during the process of encoding and retrieval? Previous studies have yielded conflicting findings, and the neural mechanisms underlying this process remain unclear.

To sum up, most previous studies only examined the influence of referential information or emotional information on word learning. There is few research on the effect of referential and emotional information on the process of novel word learning and its neural mechanisms. Besides, brain areas correlated with emotion processing, cognitive control, semantic and episodic memory probably are neural substrates for novel word learning in different referential and emotional information. Therefore, in order to examine the neural mechanisms of the effect of referential and emotional information on novel word learning, we utilized functional near-infrared spectroscopy (fNIRS) to analyze the concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HHb) in the cortex. The experiment is divided into learning stage and test stage. In the learning phase, participants combined sentences to learn novel words. In the test stage, the

participants completed semantic consistency judgement and source judgement. The research prediction is that: (1) Self-referential information is superior to other-referential information when learning novel words; (2) Referential and emotional information jointly affect the learning of novel words, that is, there is an interaction between referential and emotional information. Participants prefer to associate self-referential information with positive emotions while associating other-referential information with negative emotions, and have better learning effects on novel words under the positive self-referential contexts; (3) The effects of referential and emotional information on novel word learning are associated with the increasing activation of the prefrontal cortex and temporal lobe, particularly the DLPFC and IFG.

METHODS

Participants

The software G*Power 3.1.9.2 was utilized to calculate the minimum sample size required for the formal experiment. The number of participants, approximately 16 individuals, was determined to achieve a moderate effect size (partial $\eta^2 > 0.10$, $\alpha = 0.05$, power = 0.95). To guarantee that this study's sample size is adequate, we recruited 30 undergraduates in a university. All participants are right-handed, native Chinese speakers, aged 18 to 25 (28 females; $M = 21.50$, $SD = 2.22$), with normal or corrected-to-normal visual acuity, and they were paid a set amount to participate. Prior to their involvement, participants gave written informed consent. The university's institutional review board approved this study.

Materials

The Chinese affective words database [16] was used to select 90 Chinese two-character real words, with 30 being positive, 30 neutral, and 30 negative. 20 participants who were not involved in this experiment used a scale with ratings of 1 to 7 to rate the valence, arousal, concreteness, and familiarity of the above words (1 marked extremely negative/calm/abstract/unfamiliar, 7 marked extremely positive/aroused/concrete/familiar). The above dimensions and stroke numbers of 90 words are analyzed, and the results revealed that there were no significant differences in concreteness, familiarity and the number of strokes across all conditions ($ps > 0.1$). There were significant differences in valence across positive, neutral, and negative words, $F(2, 87) = 889.54$,

$ps < 0.001$. There was no significant difference in arousal between positive and negative words ($p = 0.85$), but there were significant differences between neutral words and emotional words ($F(2, 87) = 525.15, p < 0.001$).

To facilitate participants' acquisition of new meanings of novel words after a while of learning, random characters composed of familiar fonts and pronunciations are used to combine novel words. Therefore, we randomly selected two meaningless characters from the dictionary to form 90 novel words, each composed of two characters that have no semantic relationship with each other. We randomly coupled 90 novel words with 90 real words to form 90 pairs of real-novel word, for example, 兴奋 (xing/fen), excited, real word - 粮伸 (liang/shen), novel word. No significant differences in novel word strokes were observed under any condition ($ps > 0.1$). Table 1 shows the descriptive statistics for words.

Table 1. The descriptive statistics of the materials ($M \pm SD$).

Materials	Dimensions	Positive	Neutral	Negative
Words	Valence	6.35 ± 0.16	4.32 ± 0.66	1.80 ± 0.25
	Arousal	6.14 ± 0.30	3.23 ± 0.58	6.12 ± 0.25
	Concreteness	3.71 ± 0.37	3.58 ± 0.25	3.58 ± 0.33
	Familiarity	6.10 ± 0.21	6.03 ± 0.19	6.08 ± 0.19
	The Number of Strokes (real word)	18.63 ± 5.03	17.47 ± 3.94	18.97 ± 4.90
	The Number of Strokes (novel word)	16.03 ± 3.07	17.50 ± 4.44	16.03 ± 3.85
Sentences	Valence	6.42 ± 0.17	4.30 ± 0.74	2.06 ± 0.18
	Arousal	6.19 ± 0.24	2.59 ± 0.42	6.26 ± 0.15
	Difficulty	6.32 ± 0.12	5.93 ± 0.09	6.15 ± 0.10
	Fluency	6.35 ± 0.16	6.21 ± 0.12	6.10 ± 0.13
	Length	16.23 ± 1.28	16.13 ± 1.46	16.77 ± 1.10

Based on the target words, we compiled 90 high-constrained sentences, for example, “我/他买的彩票全中奖了，我非常____(兴奋)。” (I /he won all the lottery tickets and I was very ____ (excited).) Each sentences contained 14 to 18 Chinese characters. Another 15 participants were invited to assess the valence, arousal, difficulty, fluency and constraints of the sentences. The sentence constraint's rating was to invite participants to perform a cloze test on the sentence frame without the target word, that is, to fill in the word which is most likely to appear in the first reaction according to the sentence frame. To calculate the score of constraint, we divided the number of people who correctly inferred the words at the end of each sentence by the total number of people.

All sentences had a constraint-score above 67%, indicating easy inference of the target words from the sentences [17]. There were significant differences in valence across positive, neutral and negative sentences, $F(2, 87) = 694.93, ps < 0.001$. There was no significant difference in arousal between positive and negative sentences ($p = 0.38$), but there were significant differences between neutral and emotional sentences ($F(2, 87) = 1551.39, p < 0.001$). The analysis results of materials rating showed that the sentences were simple and fluent, and met the experimental requirements. Table 1 shows the descriptive statistics for sentences.

The ultimate stimulus comprised of two lists. We created List 2 by simply interchanging the participants of sentences from List 1. Each list comprised words from three categories of emotions and two categories of references, with 15 trials per condition. Examples of materials were shown in Table 2.

Table 2. Examples of the materials.

Referential Information	Emotional Information	Sentence (corresponding English translations)	Real Word	Novel Word
Self	Positive	我买的彩票全中奖了, 我非常____。 (I won all the lottery tickets and I was very ____.)	兴奋 (excited)	粮伸
	Neutral	我经历了生活中的种种, 一切都变得很____。 (I've been through a lot in my life, and it's all been ____.)	平淡 (plain)	洋座
	Negative	我去参加了老友的葬礼, 顿感无限____。 (I went to my old friend's funeral and I felt ____.)	伤感 (sadly)	允荷
Other	Positive	他在比赛中发挥超常, 观众们都为____。 (He played exceptionally well in the game and the crowd were ____ for him.)	高兴 (happy)	节画
	Neutral	他坐在郊外的水库边上, 内心十分____。 (He sat at the edge of the reservoir on the outskirts of the city, his mind very ____.)	沉静 (calm)	关掌
	Negative	他突然咳血, 这让他对自己的健康感到____。	担忧 (anxious)	律菜

(He suddenly coughed up blood,
which made him ____ about his
health.)

Procedures

Prior to the formal experiment, participants were assigned at random to either List 1 or List 2, taking six additional exercise trials. The matching semantic task and source testing task came after the learning task. Every task included every trial under all six conditions. We prepared the procedure with E-prime 2.0, and the experimental procedures of three tasks were shown in Figure. 1.

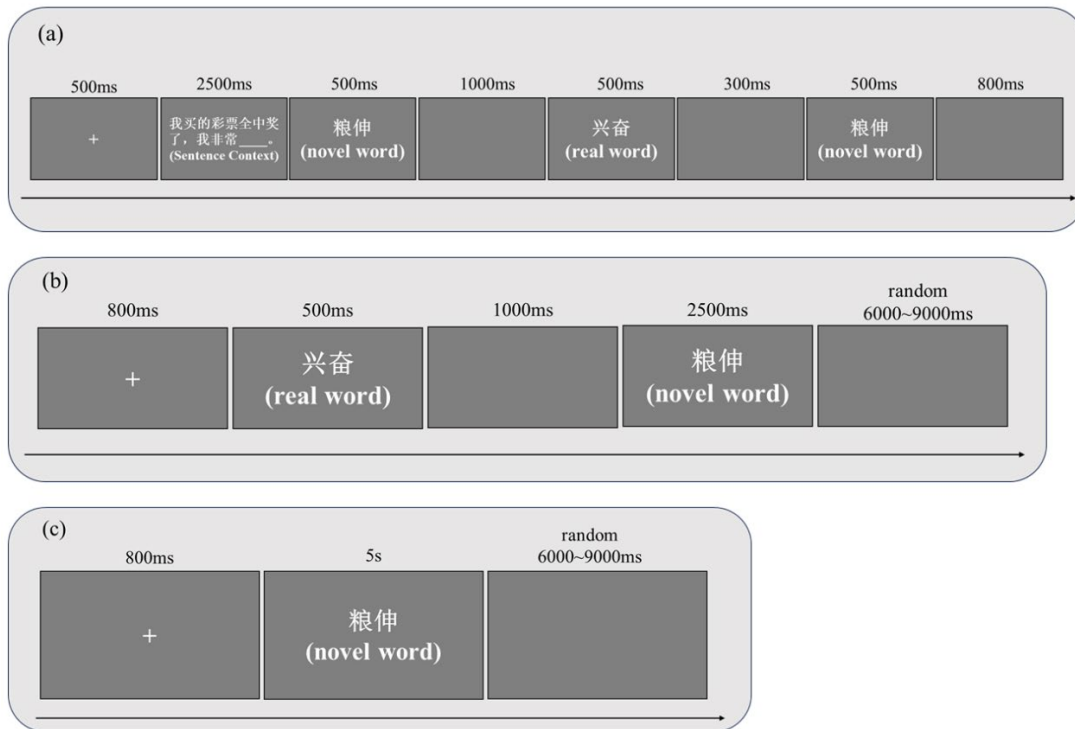


Figure 1. The experimental procedures of three tasks. *Note:* (a) illustrates the trials in the learning task; (b) illustrates the trials in the semantic consistency judgement task; (c) illustrates the trials in the source judgement task.

Learning task. In order to guarantee the learning quality, each trial was randomly and repeatedly presented twice, resulting in a total of 180 trials in a learning block. Participants were allowed to take a break following every 45 trials.

The learning task began with self-inferential or other-inferential instruction. The English equivalent of the instruction is: "In the upcoming learning task, you will see sentences related to *I* (*He*), and you should refer *I* to yourself (*He* to another person)." The learning trial started with a

500ms fixation point “+”, succeeded by the presentation of a sentence that was devoid of a key word for a duration of 2500ms. Next, we presented a novel word to learn for 500ms, followed by a 1000ms blank screen. During this period, the participants were instructed to infer the meaning of the novel word based on the sentence and then recall it. We then presented the corresponding related real word for 500ms, requiring participants to verify whether their inference was correct or incorrect. To help participants reinforce the association between the learnt word and its meaning, we presented the novel word again for 500ms following a blank screen lasting 300ms. There was an 800ms trial interval.

Semantic consistency judgement task. In the semantic consistency judgement task, participants were required to judge whether a novel word was semantically consistent with a previously presented real word. Upon the presentation of the novel word, participants were expected to respond promptly and precisely. Half of the participant selected key D to represent consistent responses, while the other half selected key K to represent inconsistent responses. The mapping of key presses and responses was reversed for the remaining participants.

Source judgement task. To identify the processing of referential information during the learning task, all participants were given a source judgement task for all 90 novel words. Participants were instructed to judge whether the novel word in the sentence subjected with either “*I*” or “*He*”. They were instructed to press the key F to indicate “*I*” and the key J to indicate “*He*”. The meaning of keys was evenly distributed among the participants.

It is important to mention that the time intervals between trials in the semantic consistency judgement task and source judgement task were modified to a random duration ranging from 6 to 9s. This adjustment was made to ensure that brain activations could revert to the baseline level [18].

Apparatus

Before the data collection commenced of each participant, we mapped the precise location (x, y, z) of the optodes relative to the brain utilizing a 3D Digitizer (CMS20EP, zebris Medical GmbH, Isny, Germany) and Zebris EIGuide (Version 1.9). The fNIRS data collection was carried out using a

continuous-wave fNIRS system (NIRScoutXP, NIRx Medical Technologies, Berlin, Germany), with 3.29Hz sampling rate. This system measured the absorption of near-infrared light at two wavelengths (785 nm & 830 nm) outfitted with 16 sources and 16 detectors, resulting in 48 channels. A channel was formed by one detector and the immediately adjacent sources in a 3.0 cm radius. We detected brain activities in frontal lobe utilizing a measuring head cap. The positions of optical optodes and channels we set were shown in Figure. 2(a). The acquisition of raw data was facilitated by NIR-STAR software (Version 15). We record behavioral data and neural data simultaneously.

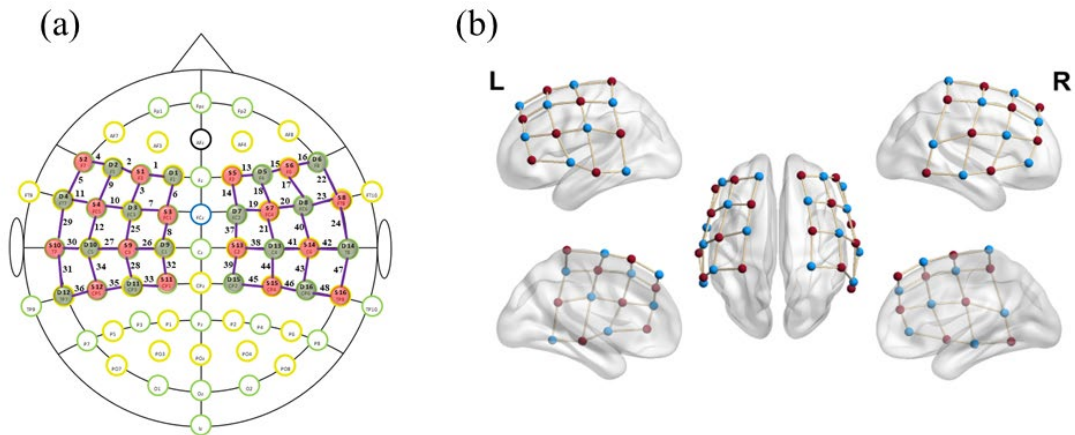


Figure. 2. Positions of optical optodes and channels. *Note:* (a) is the 2D version; (b) is the 3D version; red ones are sources and others are detectors.

Data analyses

Behavioral data analysis. Eight participants were excluded from the analysis (3 quitted and 5 for device problems), so the data of 22 participants were analyzed. The repeated measures of ANOVA were used to analyze both accuracy (ACC) and correct response time (RT) in a 2 (referential information: self, other) $\times$ 3 (emotional information: positive, neutral, negative) statistic model. RTs above and below 3 standard deviations were excluded from the analyses (2.13% of overall trials). The software SPSS version 25.0 was used for all statistical analyses.

fNIRS data analysis. We used the software MATLAB R2013b and NIRS-SPM8 toolbox to analyze the changes of oxygenated hemoglobin (HbO₂) concentration. At first, we performed a conversion of optical density data. Subsequently, we estimated the positions of each of the 48 channels within the Montreal Neurological Institute (MNI) standard brain space for each participant. The specifics were shown in Fig. 2(b). Secondly, we employed the general linear model (GLM),

which utilizes the canonical hemodynamic response function (HRF, with time and dispersion derivatives), to appraise the temporal patterns of changes in oxygenated hemoglobin concentrations (HbO₂). To account for potential global trends that could arise from physiological processes or experimental errors, such as breathing or cardiac movements, we opted for a detrending algorithm known as Wavelet-minimum description length (Wavelet-MDL). Following that, we applied low-pass filtering to the HRF. The analysis of HbO₂ data on an individual basis allowed us to calculate beta values, which reflect the level of neural activation in every experiment condition. Lastly, we analyzed all beta values through 2 (referential information: self, other) $\times$ 3 (emotional information: positive, neutral, negative) repeated measures of ANOVA. In particular, we only analyzed HbO₂, not HHb.

RESULTS

Behavior results

Semantic consistency judgement task. The ACC analyses showed the main effect of referential information ($F(1, 21) = 0.46, p = 0.50, \eta^2 = 0.02$), the main effect of emotional information ($F(2, 42) = 0.19, p = 0.83, \eta^2 = 0.01$), and the interactions between referential and emotional information ($F(2, 42) = 0.78, p = 0.46, \eta^2 = 0.04$) did not reach statistical significance. See Figure. 3(a).

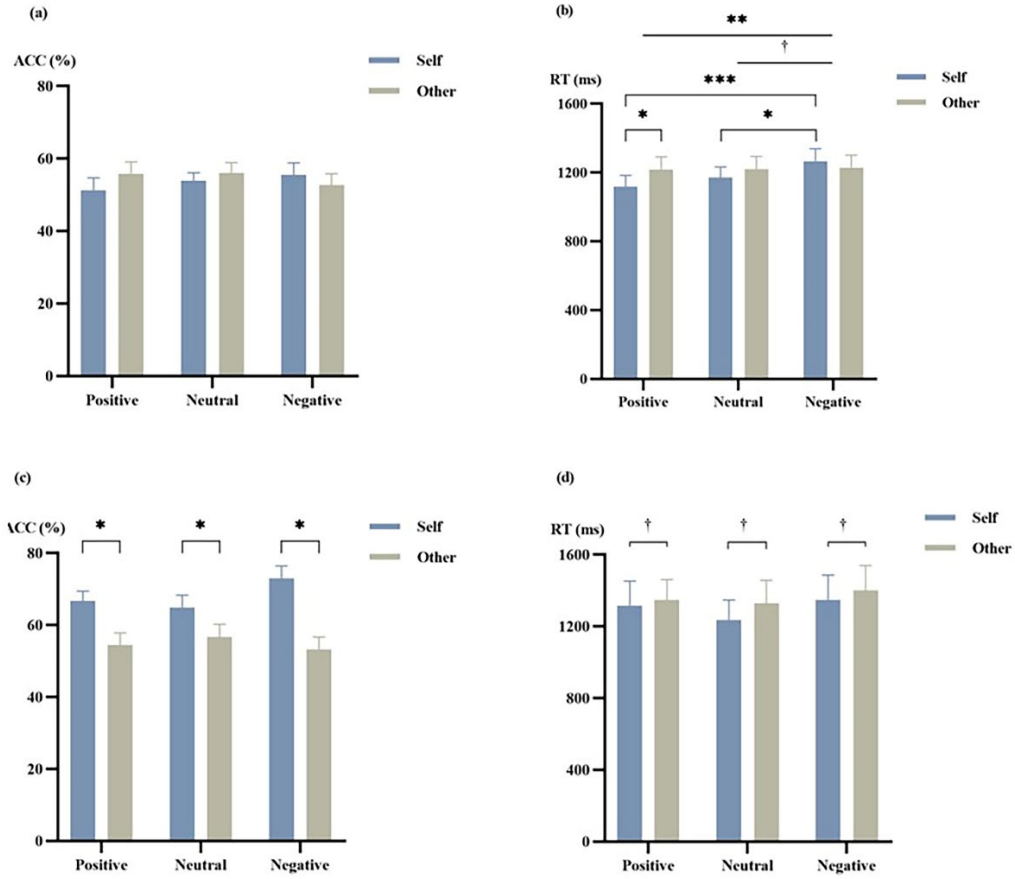


Figure. 3. The ACC and RT results for the semantic consistency judgement task and the source judgement task. *Note:* (a) is the accuracy of semantic consistency judgement task, (b) is the RT of semantic consistency judgement task; (c) is the accuracy of source judgement task, (d) is the RT of source judgement task; the error bars indicate the standard error (SE); † means marginally significant, * $p < .05$, ** $p < .01$, *** $p < .001$.

The RT analyses showed a significant main effect of emotional information, $F(2, 42) = 6.17$, $p = 0.004$, $\eta^2 = 0.23$. Relative to negative sentences (1248 ± 69 ms), participants showed a significant decrease in RT to the novel word learned in positive sentences (1168 ± 66 ms) ($p = 0.01$) and a marginally significant decrease in neutral sentences (1195 ± 64 ms), $p = 0.08$. The differences between neutral and positive sentences were not significant, $p = 0.86$. The interaction between referential and emotional information was marginally significant, $F(2, 42) = 2.99$, $p = 0.06$, $\eta^2 = 0.13$. Simple effect analyses showed that participants response longer to the self-referential condition of novel words learned in negative sentences (1266 ± 72 ms) than positive (1117 ± 66 ms) ($p = 0.000$) and neutral sentences (1171 ± 61 ms) ($p = 0.02$), whereas differences between positive and neutral sentences were not significant ($p = 0.20$). On the contrary, participants didn't show

significant difference in RT to the other-referential condition of novel words learned across positive (1218 ± 73 ms), neutral (1220 ± 74 ms) or negative sentences (1229 ± 71 ms), $ps > 0.73$. Besides, only for the novel words learned in positive sentences, participants showed significantly longer RT in self-referential condition than other-referential, $p = 0.03$. The main effect of referential information did not reach statistical significance, $F(1, 21) = 2.68$, $p = 0.12$, $\eta^2 = 0.11$. See Figure. 3(b).

Source judgement task. The ACC analyses showed a significant main effect of referential information, $F(1, 21) = 8.65$, $p = 0.01$, $\eta^2 = 0.29$. Participants had greater accuracy in retrieving the referential information of the novel words learned from self-reference (0.68 ± 0.03) compared to those learned through other-reference (0.55 ± 0.03), $p = 0.01$. The main effect of emotional information was not statistically significant, $F(2, 42) = 0.70$, $p = 0.50$, $\eta^2 = 0.03$. The interaction between referential and emotional information was not statistically significant, $F(2, 42) = 2.11$, $p = 0.13$, $\eta^2 = 0.09$. See Figure. 3(c).

The results of the RT analyses showed that the main effect of referential information was marginally significant, $F(1, 21) = 3.79$, $p = 0.07$, $\eta^2 = 0.15$. Participants had a longer RT of novel words detected in self-referential (1301 ± 125 ms) than other-referential condition (1359 ± 120 ms). There was no statistically significant main effect for the emotional information ($F(2, 42) = 2.36$, $p = 0.11$, $\eta^2 = 0.10$), or the interaction between referential and emotional information ($F(2, 42) = 0.29$, $p = 0.68$, $\eta^2 = 0.01$). See Figure. 3(d).

fNIRS results

Semantic consistency judgement task. Significant main effects of referential information were observed in CH26 and CH36. In CH26, which primarily covered the left pre-motor and supplementary motor cortex, it was observed that there was a greater activation in the other-reference compared to the self-reference, $F(1, 21) = 5.29$, $p = 0.03$, $\eta^2 = 0.20$. See Figure. 4(a). In CH36, which primarily covered the left superior temporal gyrus, it was observed that there was a marginally greater activation in the self-reference compared to the other-reference, $F(1, 21) = 3.10$, $p = 0.09$, $\eta^2 = 0.13$. See Figure. 4(b). The main effect of emotional information was not observed.

The marginally significant interaction of referential and emotional information was mainly observed in the left middle temporal gyrus underlying CH31, $F(2, 42) = 2.84, p = 0.07, \eta^2 = 0.12$. Simple effect analysis showed that in self-referential condition, effects of emotion were not observed, while in other-referential condition, activation level of novel words learned in positive sentences were marginally greater than neutral sentences, $p = 0.05$. See Figure. 4(c). The corresponding statistical values of channels were showed in Table 3. The corresponding brain areas that underlie the channels that showed significant effects were presented in Table 4.

Table 3. The statistical values of main effects and interactions in the channels of semantic consistency judgement task and source judgement task.

	Channel	Referential information			Emotional information			The interaction of referential and emotional information		
		F	p	η^2	F	p	η^2	F	p	η^2
Semantic consistency judgement task	CH26	5.29	0.03*	0.20	0.64	0.54	0.03	2.27	0.12	0.10
	CH31	0.21	0.65	0.01	0.11	0.89	0.01	2.84	0.07 [†]	0.12
	CH36	3.10	0.09 [†]	0.13	0.08	0.92	0.00	1.06	0.36	0.05
Source judgement task	CH01	3.65	0.07 [†]	0.15	0.09	0.92	0.00	0.17	0.84	0.01
	CH02	5.19	0.03*	0.20	2.36	0.12	0.10	0.35	0.71	0.02
	CH05	0.51	0.48	0.02	4.03	0.04*	0.16	7.66	0.001***	0.27
	CH18	7.67	0.01**	0.27	0.61	0.55	0.03	1.32	0.28	0.06
	CH19	5.44	0.03*	0.21	0.89	0.42	0.04	0.64	0.53	0.03
	CH20	3.64	0.07 [†]	0.15	0.51	0.60	0.02	0.63	0.54	0.03
	CH21	3.39	0.08 [†]	0.14	0.06	0.94	0.00	0.50	0.61	0.02
	CH23	1.50	0.23	0.07	3.67	0.05*	0.15	0.94	0.40	0.04
	CH24	0.43	0.52	0.02	3.24	0.07 [†]	0.13	2.19	0.13	0.09
	CH26	3.32	0.08 [†]	0.13	0.57	0.57	0.03	0.75	0.48	0.03
	CH27	1.23	0.28	0.06	3.89	0.03*	0.16	0.04	0.96	0.00
	CH28	3.92	0.06 [†]	0.16	1.47	0.24	0.07	0.61	0.55	0.03
	CH29	0.36	0.55	0.02	2.72	0.10	0.12	5.53	0.01**	0.21
	CH30	0.05	0.83	0.00	3.30	0.05*	0.14	1.26	0.30	0.06
	CH31	0.48	0.50	0.02	3.57	0.05*	0.15	2.00	0.15	0.09
	CH32	4.25	0.05*	0.17	0.89	0.38	0.04	1.07	0.35	0.05
	CH34	0.53	0.48	0.03	3.39	0.07 [†]	0.14	1.04	0.36	0.05
	CH35	4.45	0.05*	0.18	3.46	0.07 [†]	0.14	0.07	0.84	0.00
	CH43	0.45	0.51	0.02	2.71	0.09 [†]	0.11	0.17	0.77	0.01
	CH44	0.91	0.35	0.04	2.87	0.07 [†]	0.12	0.48	0.62	0.02
	CH45	4.35	0.05*	0.17	1.02	0.37	0.05	0.10	0.91	0.01
	CH47	1.43	0.25	0.06	1.81	0.19	0.08	3.85	0.03*	0.16

Note: * $p < .05$, ** $p < .01$, *** $p < .001$, [†] means marginally significant.

Source judgement task. The main effect of referential information was significantly observed in CH02 ($F(1, 21) = 5.19, p = 0.03, \eta^2 = 0.20$), CH18 ($F(1, 21) = 7.67, p = 0.01, \eta^2 = 0.27$), CH19 ($F(1, 21) = 5.44, p = 0.03, \eta^2 = 0.21$), CH35 ($F(1, 21) = 4.45, p = 0.05, \eta^2 = 0.18$) and CH45 ($F(1, 21) = 4.35, p = 0.05, \eta^2 = 0.17$). Also, the main effect of referential information was marginally significantly observed in CH01 ($F(1, 21) = 3.65, p = 0.07, \eta^2 = 0.15$), CH20 ($F(1, 21) = 3.64, p = 0.07, \eta^2 = 0.15$), CH21 ($F(1, 21) = 3.39, p = 0.08, \eta^2 = 0.14$), CH26 ($F(1, 21) = 3.32, p = 0.08, \eta^2 = 0.14$), CH28 ($F(1, 21) = 3.92, p = 0.06, \eta^2 = 0.16$) and CH32 ($F(1, 21) = 4.25, p = 0.05, \eta^2 = 0.17$). The activation patterns were similar across these 11 channels, which included brain areas such as the DLPFC, and the pre-motor and supplementary motor cortex. As an instance, compared to the other-reference, it showed a smaller activation for self-reference in CH02, which primarily covered the left DLPFC. See Figure. 4(d).

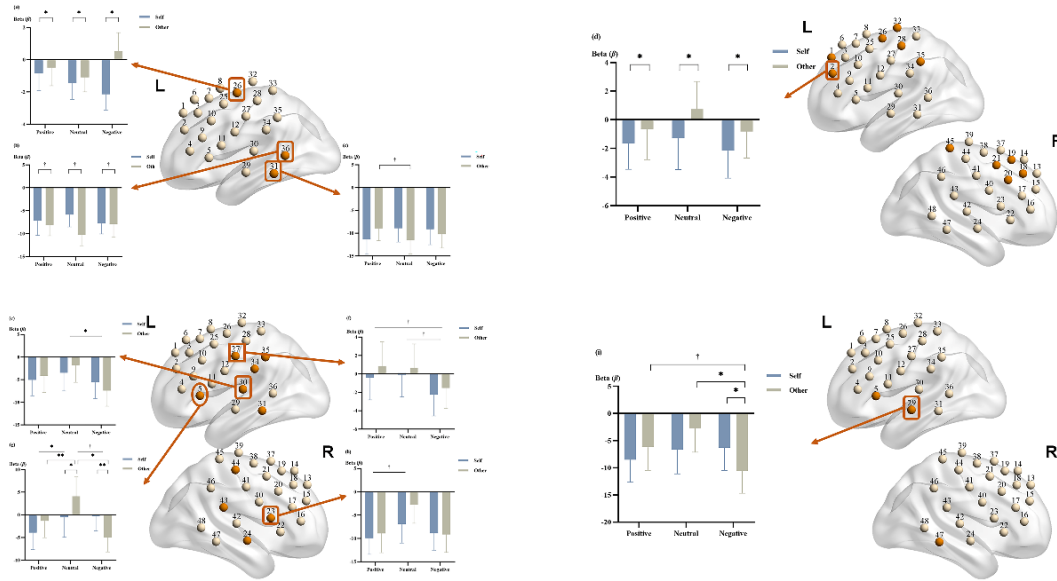


Figure. 4. The significant effects observed in the semantic consistency judgement task and the source judgement task. *Note:* (a) is the significant main effect of referential information observed in CH26 in the semantic consistency judgement task; (b) is the significant main effect of referential information observed in CH36 in the semantic consistency judgement task; (c) is the significant interaction of referential and emotional information observed in CH31 in the semantic consistency judgement task; (d) is the significant main effect of referential information observed in CH2 in the source judgement task; (e) is the significant main effect of emotional information observed in CH30 in the source judgement task; (f) is the significant main effect of emotional information observed in CH27 in the source judgement task; (g) is the significant main effect of emotional information and the significant interaction of referential and emotional information observed in CH5 in the source

judgement task; (h) is the significant main effect of emotional information observed in CH23 in the source judgement task; and (i) is the significant interaction of referential and emotional information observed in CH29 in the source judgement task; the error bars indicate the standard error (*SE*); † means marginally significant, * $p < .05$, ** $p < .01$.

The main effect of emotional information was significantly observed in CH05 ($F(2, 42) = 4.03$, $p = 0.04$, $\eta^2 = 0.16$), CH27 ($F(2, 42) = 3.89$, $p = 0.03$, $\eta^2 = 0.16$) and CH30 ($F(2, 42) = 3.30$, $p = 0.05$, $\eta^2 = 0.14$). Also, the main effect of emotional information was marginally significantly observed in CH23 ($F(2, 42) = 3.67$, $p = 0.04$, $\eta^2 = 0.16$), CH24 ($F(2, 42) = 3.24$, $p = 0.07$, $\eta^2 = 0.13$), CH31 ($F(2, 42) = 3.57$, $p = 0.05$, $\eta^2 = 0.15$), CH34 ($F(2, 42) = 3.39$, $p = 0.07$, $\eta^2 = 0.14$), CH35 ($F(2, 42) = 3.46$, $p = 0.07$, $\eta^2 = 0.14$), CH43 ($F(2, 42) = 2.71$, $p = 0.09$, $\eta^2 = 0.11$) and CH44 ($F(2, 42) = 2.87$, $p = 0.07$, $\eta^2 = 0.12$). It was worth noting that 9 of those channels (CH05, CH24, CH27, CH30, CH31, CH34, CH35, CH43, and CH44) shared a fundamentally similar activation pattern, under which were the anterior part (BA45, Pars triangularis Broca's area) of inferior frontal gyrus (IFG), the middle temporal gyrus, the superior temporal gyrus, the pre-motor and supplementary motor cortex, and the supramarginal gyrus part of Wernicke's area. As an instance, in CH30, which primarily covered the left superior temporal gyrus, it was displayed that the retrieval of novel words learning in negative sentences induced smaller activation than those in neutral sentences, $p = 0.04$. See Figure. 4(e). Besides, it is notable that, in addition to sharing this basic activation pattern similar to CH30, the retrieval of novel words learning in positive sentences induced greater activation compared to negative sentences in CH27 ($p = 0.08$) and CH34 ($p = 0.03$). See Figure. 4(f) for an example of CH27, which primarily covered the left pre-motor and supplementary motor cortex. It also displayed that the retrieval of novel words learned in positive sentences induced smaller activation compared to neutral sentences in CH05 ($p = 0.02$) and CH35 ($p = 0.09$). See Figure. 4(g) for an example of CH05, which primarily covered the left anterior part of IFG. Furthermore, in CH23, which primarily covered the right posterior part (BA44, Pars opercularis, part of Broca's area) of IFG, it was only observed that the retrieval of novel words learned in positive sentences induced smaller activation compared to neutral sentences, $p = 0.06$. See Figure. 4(h).

Moreover, the significant interaction of referential and emotional information was observed in

CH05 ($F(2, 42) = 7.66, p = 0.001, \eta^2 = 0.27$), CH29 ($F(2, 42) = 5.53, p = 0.01, \eta^2 = 0.21$) and CH47 ($F(2, 42) = 3.85, p = 0.03, \eta^2 = 0.16$), which mainly covered the anterior part of IFG and the middle temporal gyrus. Notably, the simple effect analysis for these 3 channels found that they shared a similar activation pattern. The basic activation pattern showed that in other-reference, compared with neutral sentences, the retrieval of referential information for novel words learning in negative sentences caused smaller activation, $ps < 0.05$. In addition to the basic activation pattern, the simple effect analysis for CH05 displayed that in other-reference, compared with neutral sentences, the retrieval of the referential information for novel words learning in positive sentences caused smaller activation, $p = 0.009$, see Figure. 4(g); the simple effects analysis for CH29 and CH47 also displayed that in other-reference, compared with negative sentences, the retrieval of the referential information for novel words learning in positive sentences caused marginally greater activation, $ps = 0.09$. See Figure. 4(i) for an example of CH29, which primarily covered the middle temporal gyrus. The corresponding statistical values of channels were showed in Table 3. The corresponding brain areas that underlie the channels that showed significant effects were presented in Table 4.

Table 4. The corresponding brain areas underlying the channels showing significant main effects of the semantic consistency judgement task and the source judgement task.

	Channel	Coordinate			BA	Brain Area	Coverage Rate
		X	Y	Z			
Semantic consistency judgement task	CH26	-41	-5	64	6	Pre-Motor and Supplementary Motor Cortex	0.96947
	CH31	-70	-38	-8	21	Middle Temporal Gyrus	0.98754
	CH36	-69	-48	8	21	Middle Temporal Gyrus	0.34416
					22	Superior Temporal Gyrus	0.65584
Source judgement task	CH01	-27	43	46	9	Dorsolateral Prefrontal Cortex	0.99552
	CH02	-45	42	31	9	Dorsolateral Prefrontal Cortex	0.25941
					46	Dorsolateral Prefrontal Cortex	0.6569
	CH05	-58	20	6	44	Pars opercularis, part of Broca's area	0.18567
					45	Pars triangularis Broca's area	0.50489
					47	Inferior Prefrontal Gyrus	0.21498

CH18	45	33	44	9	Dorsolateral Prefrontal Cortex	0.61161
				44	Pars opercularis, part of Broca's area	0.13393
				45	Pars triangularis Broca's area	0.13839
				46	Dorsolateral Prefrontal Cortex	0.11607
CH19	40	22	57	8	Includes Frontal eye fields	0.2766
				9	Dorsolateral prefrontal cortex	0.7234
CH20	55	19	38	8	Includes Frontal eye fields	0.20438
				9	Dorsolateral prefrontal cortex	0.76642
CH21	51	8	52	6	Pre-Motor and Supplementary Motor Cortex	0.66803
				9	Dorsolateral Prefrontal Cortex	0.33197
CH23	64	12	13	6	Pre-Motor and Supplementary Motor Cortex	0.19156
				44	Pars opercularis, part of Broca's area	0.59091
				45	Pars triangularis Broca's area	0.18831
CH24	71	-10	-8	21	Middle Temporal Gyrus	0.99357
CH26	-41	-5	64	6	Pre-Motor and Supplementary Motor Cortex	0.96947
CH27	-62	-13	43	3	Primary Somatosensory Cortex	0.175
				4	Primary Motor Cortex	0.1
				6	Pre-Motor and Supplementary Motor Cortex	0.69286
CH28	-56	-23	57	1	Primary Somatosensory Cortex	0.29555
				2	Primary Somatosensory Cortex	0.40486
				3	Primary Somatosensory Cortex	0.19028
CH29	-69	-13	-7	21	Middle Temporal Gyrus	0.90823
CH30	-68	-20	12	22	Superior Temporal Gyrus	0.8354
CH31	-70	-38	-8	21	Middle Temporal Gyrus	0.98754
CH32	-31	-19	74	4	Primary Motor Cortex	0.19529
				6	Pre-Motor and Supplementary Motor Cortex	0.80471

CH34	-69	-31	31	2	Primary Somatosensory Cortex	0.13313
				40	Supramarginal Gyrus part of Wernicke's area	0.83282
CH35	-65	-41	42	40	Supramarginal Gyrus part of Wernicke's area	1
CH43	71	-32	23	22	Superior Temporal Gyrus	0.18125
				40	Supramarginal Gyrus part of Wernicke's area	0.63438
				42	Primary and Auditory Association Cortex	0.17813
CH44	56	-21	58	1	Primary Somatosensory Cortex	0.2874
				2	Primary Somatosensory Cortex	0.25197
				3	Primary Somatosensory Cortex	0.38583
CH45	43	-36	68	1	Primary Somatosensory Cortex	0.21723
				2	Primary Somatosensory Cortex	0.31086
				3	Primary Somatosensory Cortex	0.20225
				4	Primary Motor Cortex	0.10112
CH47	72	-39	-9	21	Middle Temporal Gyrus	0.91318

Note: The brain areas with a coverage higher than 0.1 were listed. “BA” is an abbreviation for Brodmann Area.

DISCUSSION

In this study, fNIRS technique was used to investigate the effect of referential and emotional information on novel word learning and its neural mechanisms. The results showed that: First, the referential information affected the novel word learning, and the self-reference could facilitate novel word learning; Second, the interaction between referential and emotional information was significant; Third, the activation of DLPFC and IFG was associated with self-referential advantage in novel word learning, and the superior temporal gyrus (STG), the middle temporal gyrus (MTG), along with the pre-motor and supplementary motor cortex, were the key regions affecting novel word learning activities. The above findings are discussed below.

The facilitating effect of self-referential information

In this study, the self-reference effect was consistently observed in both the semantic consistency judgement task and source judgement task, showing a robust self-referential advantage in retrieving semantic information and encoding source memory of novel words. Behavioral results showed that the performance of self-referential novel word is significantly greater than that of other-reference. It can be seen that compared with other-reference, self-reference does have an important impact on the coding process, resulting in clearer memories and showing self-reference memory advantages. The fNIRS results showed that, compared to self-reference, novel words learned under other-referential sentences caused greater activation mainly in the DLPFC, the pre-motor and supplementary motor cortex, as well as the supramarginal gyrus part of Wernicke's area.

Researchers have pointed out that DLPFC serve as the neural basis for general executive function in language processing and part of the attention control network, which is responsible for managing individual attention during emotional regulation [19]. We speculate that under self-reference, the directivity and concentration of individuals' attention to novel words are greatly improved, and the coding quality is improved. In the test process, individuals extract more detailed or deeper information about new words. Thus, the activation of DLPFC may reflect a more refined and complex representation of novel words learned under self-referential conditions. This study aligns with previous studies [20], indicating that the advantage of self-reference in source memory remains stable, and compared with item memory, the SRE is more pronounced.

The effect of emotional information

Behavioral results from the semantic consistency judgement task show that the RT to positive novel words is significant shorter compared to negative novel words. This indicates that positive information promotes the acquisition of novel words, while negative information hinders it. These results align with previous research [9; 12]. The main effect of emotional information was observed at the neural level in the source judgement task. Compared to positive and neutral sentences, the MTG, STG, the anterior and posterior part of the IFG, and the left pre-motor and supplementary motor cortex showed the least degree of activation in the negative sentences, indicating that

participants allocated less cognitive resources to the novel words learned in the negative contexts and relatively more cognitive resources to the novel words learned in the positive contexts.

Studies have demonstrated that the activation of IFG is important in word learning and that it is highly sensitive towards the contextual information present in sentences [21]. The left IFG, also known as Broca's area, is a key brain region for language processing, with the pars opercularis (BA44) primarily associated with word generation and phonological processing, and the pars triangularis (BA45) primarily associated with semantic processing [22]. Therefore, we think that participants in this experiment extract emotional information from sentences and intentionally establish additional associations with novel words, thus triggering activation of related neural activities in the anterior and posterior part of IFG. Additionally, the pre-motor and supplementary motor cortex is activated. Researchers have also found that activities related to learning and cognitive control trigger activation of the pre-motor and supplementary motor cortex [23]. This study can provide new empirical support for the discovery that the pre-motor and supplementary motor cortex are brain regions that affect language learning activities.

Referential and emotional information jointly affect novel word learning

Taking into account the interaction of neural activation patterns observed in this study, we believe that referential and emotional information may not be independent of one another and that emotional information are regulated by referential information.

We observed the interaction between referential and emotional information from the RT at behavioral level in the semantic consistency judgment task, showing a self-positive bias in novel word learning. This could be because, in the self-referential sentences, participants associate positive emotions with themselves and thus allocate more attention to processing words. At neural level, however, we observed the interaction between referential and emotional information in both tasks, indicating that there may be an other-negative bias in novel word learning. In addition, we observed the interaction in the MTG and the anterior part of IFG, with decreased activation in negative other-referential sentences. The decreased activation observed in the source judgement task indicated that participants had better integration of negative other-referential sentences and novel words in their episodic memory. In the temporal lobe, the MTG and STG, including the Wernicke's

area, are primarily responsible for processing word meanings in reading and are also the main brain regions involved in language learning [24]. It has been found that participants with higher learning efficiency showed more activation in the left MTG and STG and less activation in the right IFG, indicating that the MTG and STG could predict the efficiency of novel word learning [25]. The results of the present study similarly support the finding that temporal lobe is a part of the language network, and the MTG and STG play an important role in novel word learning.

Collectively, combining the behavioral and neural data, it is reasonable to speculate that recalling negative positive self-referential information and other-referential information are easier for individuals, resulting in a more consistent and harmonious cognitive control pattern. These results provide support for the self-positive bias and other-negative bias, indicating that the referential and emotional information jointly affect the novel word learning.

Limitations and future work

Present work has a few limitations. First of all, based on previous studies and considering the possible burden of fNIRS technology equipment on participants, we set the number of repetitions of participants' learning of novel words to two times. The experimental task may be too difficult, so the research results must be treated with caution. Secondly, our experiment was limited to the sentence level, disregarding the potential influence of paragraph and text, which are also rich resources of information. Future work can delve deeper into paragraphs and discourses. Finally, the limitations of the fNIRS method have prevented a full study of the brain network involved in novel word learning, and methods and techniques with more thorough research on the neural mechanisms can be used in the future, such as fMRI.

CONCLUSIONS

This study shows that self-referential information can promote lexical coding of novel words, form more refined semantic representation, and contribute to word learning. Therefore, employing self-reference as a coding strategy proves to be highly effective in the acquisition of novel word. Secondly, the interaction between referential and emotional information indicated that both of them jointly affect the novel word learning, resulting in a bias towards self-positive and other-negative.

Moreover, these effects of referential and emotional information are associated with neural activities in the dorsolateral prefrontal cortex (DLPFC), the inferior frontal gyrus (IFG), the middle temporal gyrus (MTG), the superior temporal gyrus (STG), and the pre-motor and supplementary motor cortex. It can be seen from the above that the DLPFC is related to the advantage of self-referential word learning. Additionally, the anterior part of IFG, and MTG are the key regions affecting novel word learning.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Shan Li: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Xue Sui:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Yanbo Hu:** Supervision, Project administration. **Yutong Li:** Investigation, Data curation, Supervision, Funding acquisition.

CONFLICTS OF INTEREST

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

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