fMRI Evidence Reveals Emotional Biases in Bilingual Decision Making

Yuying He^{a,b}, Francesco Margoni^c, Yanjing Wu^d, Huanhuan Liu^{a,b}

^a Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University,
China.

^b Key Laboratory of Brain and Cognitive Neuroscience, Liaoning Province, China.

^c Department of Psychology and Cognitive Science, University of Trento, Italy.

^d Faculty of Foreign Languages, Ningbo University, China.

Author Note

This research was supported by a Grant from National Natural Science Foundation of China Youth Fund (31700991) and China Postdoctoral Science Foundation (2017M621158).

Correspondence concerning this article should be addressed to Huanhuan Liu, Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, 116029, China. Telephone: 0411-8215-9733 Email: abcde69503@126.com

Abstract

Previous research has suggested that foreign language effect on decision making can be partially explained by a reduction in emotional response in the second language. In this fMRI study, we aimed at elucidating the neural mechanisms underpinning the interaction between language and emotion and its influence on decision making. Across multiple trials, Chinese-English bilinguals were asked to decide whether to gamble or not in a Gambling task and received feedbacks in either L1 (Chinese) or L2 (English). If they gambled, feedbacks were either positively or negatively valenced words; if they did not gamble, feedback was the word 'safe'. We assessed how emotionally valenced words were processed in the two languages and how this processing influenced subsequent decision making. Overall, we found evidence that in L2 context, but not in L1 context, loss aversion was mediated by the dorsolateral prefrontal cortex which also showed strong functional connectivity with the visual cortex, suggesting an avoidance mechanism for negative stimuli in L2. However, we also found an enhanced response to positive feedbacks in L2 compared to L1, as evidenced by greater activation of the hippocampus for win feedbacks compared to safe feedbacks in L2 eventually resulting in a greater tendency to gamble. Foreign language therefore influenced decision making by both reducing emotional response to negative stimuli and enhancing emotional response to positive stimuli. This study helps unveiling the neural bases of the interaction between language and emotion.

Keywords: bilingualism; emotion; foreign language; dmPFC; dlPFC; hippocampus

fMRI Evidence Reveals Emotional Biases in Bilingual Decision Making

Prior work has suggested that bilinguals have different access to emotion depending on whether they use their first native language (L1) or their second foreign language (L2). Recounting a traumatic memory, saying “I love you” or reading a taboo word are all examples of processes that have been found to be less automatic and less affected by emotional activation in L2 than in L1 (Caldwell-Harris, 2014; Caldwell-Harris et al., 2013; Fan et al., 2016; Ivaz et al., 2016; Pavlenko, 2012; Sulpizio et al., 2019). This language effect influences memory too: Foreign language emotional words are recalled worse than native language ones (Baumeister et al., 2017; El-Dakhs & Altarriba, 2018, 2019; Jay et al., 2008; Talmi & Moscovitch, 2004; Vidal et al., 2019).

Foreign language has also been shown to affect decision making and reduce decision biases likely because, it has been suggested, it increases emotional distance (Keysar et al., 2012). Recent work has indeed found that a foreign language context leads to a more rational decision making in monetary tasks (Gao et al., 2015; Liu et al., 2020; see also Zheng et al., 2020). Moreover, processing information in L2 as opposed to L1 influences moral judgment, although it is not clear whether it does so by reducing activation of social and moral norms (Geipel et al., 2015a, 2015b) or by attenuating emotional activation (Geipel et al., 2016). Further strengthening the hypothesis that L2 affects decision making largely by influencing emotional activation, it was reported that foreign language effect in decision making is present only in tasks in which participants have to make a decision where emotion may have a causal role (Costa et al. 2014; Vives et al., 2018).

Thus, understanding the relationship between language and emotion is key to uncover the mechanism underlying the foreign language effect on decision making. The current study aimed at going in this direction by investigating at the neural level how emotionally valenced stimuli influence decision making differently depending on the language context.

An embodied approach to language has been used to explain differences in access to emotion between L1 and L2: while L1 is mainly acquired through real-life social interactions where emotional words are associated with psychophysiological states, L2 is acquired in contexts almost devoid of emotions such as classroom environments (Caldwell-Harris, 2014; Dudschig et al., 2014; Foroni, 2015; Pavlenko, 2012; Sheikh & Titone, 2015; Vukovic & Shtyrov, 2014; see also Cheng et al., 2020). To give an example, the word ‘sad’ in L1 is likely linked to high emotional and physiological arousal associated to real-life negative events such as having lost a beloved toy during childhood, whereas in L2 it likely fails to be grounded in autobiographic memory or linked to emotional arousal (Cox & Zlupko, 2019; Matsumoto & Stanny, 2006; Schrauf & Rubin, 2000; Woumans et al., 2020). A decontextualized learning thus results in affective disembodiment and emotional distance.

According to this approach, one should predict a reduction in access to emotion for both L2 negative and L2 positive words. However, a number of studies have reported a reduced access to emotion in L2 for negative words but not for positive words (Caldwell-Harris, 2014; Sheikh & Titone, 2015; Wu & Thierry, 2012). First, a study found that when L2 positive and neutral words were presented to participants, their L1

translation equivalents were automatically activated, whereas negative L2 words failed to activate their L1 equivalents (Wu & Thierry, 2012). Authors posited that such interaction between language and emotion may be the outcome of a mechanism that in L2 protects from cognitive loading by automatically suppress the full processing of negative and potentially distressing information. Thus, negative content processed in L2 seems to trigger inhibitory mechanisms that suppress the full lexical-semantic integration and, in a way, ‘save your heart’ by preventing strong emotional activation (Jończyk et al., 2016; Wu & Thierry, 2012). In this sense, given that processing of L2 can be already demanding, the mind automatically avoids further cognitive loading due to emotional reactions to negative stimuli triggered by the translation of L2 words in L1, and does not activate the translation equivalents.

Second, in L2 a preference for positive words may exist. According to the positive bias hypothesis, L2 enhances rather than reduces emotional reaction to positive stimuli (Caldwell-Harris, 2014; Sheikh & Titone, 2016). A study on bilinguals’ decisions whether to bet or not in a Gamling task found that the reward brain networks response to positive feedbacks (e.g., ‘wonderful’ after a win) was exaggerated in L2 compared to L1, suggesting that positive words in L2 amplify positive emotions (Zheng et al., 2020). The study did not find a corresponding reduction in negative emotions for L2 negative words compared to L1 negative words, but this effect is reported in other clinical and electrophysiological work (Chen et al., 2015; Dewaele & Costa, 2013; Jończyk et al., 2016; Opitz & Degner, 2012; Woumans et al., 2020). A possibility is therefore that two mechanisms coexist in L2 word processing, one that suppresses full

access to negative emotions and the other that facilitates access to positive emotions.

This Study

In the present study we used functional magnetic resonance imaging (fMRI) to elucidate the neural mechanisms underpinning the interplay between language and emotion in economic decision making. Participants played a Gambling task where they had to decide whether to bet or not. After each trial, they received either positive or negative emotional feedbacks (e.g., ‘wonderful’ or ‘terrible’) depending on whether they had lost or won, respectively. Importantly, these feedbacks were presented either in L1 (Chinese) or in L2 (English). We thus manipulated both the valence of the emotional feedbacks and the language in which feedbacks were presented, and investigated how these factors and their interaction influence at the behavioral and neural level participants’ word processing and their decision making.

The embodiment approach discussed above would predict that, compared to L1 feedbacks, both positive and negative L2 feedbacks activate less the brain regions implicated in emotion or reward and the functional connectivity in regions responsible for emotion processing. By contrast, the positive bias hypothesis and its recent protective mechanism version would predict that, compared to L1 words, L2 negative words will activate more areas associated with inhibitory control whereas L2 positive words will elicit stronger positive feelings and thus activate more regions related to emotion processing. Finally, we assessed how brain activation differences between the two languages were associated with participants’ decision making.

Method

Participants

Twenty-three unbalanced Chinese-English (L1-L2) bilingual students at Liaoning Normal University participated in this study. They were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychological impairments. Behavioral and fMRI data from three participants were excluded, because of either excessive head motion during scanning or because they completed an insufficient number of trials (< 10). Final sample consisted of 20 participants (9 male; $M = 22.00 \pm 1.90$ years). The research protocol was approved by the Ethics Committee of the Research Center of Brain and Cognitive Neuroscience at Liaoning Normal University.

Participants had learned English for 12 years on average (self-reported mean age of L2 acquisition was 9.25 ± 2.66 years, Min = 5, Max = 13 years). Their English usage was mainly limited to classroom context. Language proficiency was assessed with the Oxford Placement Test (OPT; Allan, 2004), by administering 25 multiple choice questions and a cloze test (see Table 1 for mean scores). Participants also self-rated their language skills using a six-point scale that ranged from 1 (= *no knowledge of L1/L2*) to 6 (= *perfect knowledge*). Four paired t-tests revealed that proficiency ratings were significantly higher for L1 than for L2 in listening, speaking, reading, and writing, $t(19) \geq 5.11$, $ps < .001$.

Table 1*Participants' Characteristics (Mean $\pm$ SD).*

	L1	L2
Listening	5.60 $\pm$ 0.66	3.30 $\pm$ 0.60
Speaking	5.05 $\pm$ 0.81	3.35 $\pm$ 0.60
Reading	4.45 $\pm$ 1.02	2.75 $\pm$ 0.94
Writing	5.10 $\pm$ 1.08	3.30 $\pm$ 0.91
OPT		36.3 $\pm$ 3.31

Note: OPT = Oxford Placement Test (maximum score = 50).

Materials

In each trial of the Gambling task, participants were presented with a picture of an Ace playing card which had two dialogue boxes above it, one on the left and the other on the right (see Figure 1a). The four suit symbols (heart, diamond, spade, club) of the card were randomly presented across trials. In each dialogue box, a value (varying from 15 to 95) indicated the winning probability of the game trial. If the two boxes contained the same value (e.g., left 40, right 40), the winning probability was indicated by that value. If the two boxes contained different numbers (e.g., left 40, right 80), the winning probability could have been either the value on the left or the one on the right. If, instead, the boxes contained a range of values (e.g., left 40-80, right 40-80), the winning probability was ambiguous as it could have been any values within the range. Types of trial and probability values were presented pseudorandomly.

In each trial, after choosing whether to gamble, participants received a feedback

either in L1 or in L2 (see Table 2). If they gambled, they received a positive feedback when winning and a negative one when losing. We selected five positively valenced words for winning feedbacks and five negatively valenced words for losing feedbacks. If participants did not gamble, the word ‘safe’ (or its translation equivalent in Chinese, 稳妥) was used as feedback. English words had high and homogenous lexical frequency (Coltheart, 1981), differed in affective valence ($M_{Positive} = 7.44$, $M_{Negative} = 3.31$; $t(8) = 7.07$, $p < .001$) but not in arousal ($M_{Positive} = 4.19$, $M_{Negative} = 4.49$; $t(8) = .73$, $p = .490$; Warriner et al., 2013).

Table 2

Feedback Words Used in the Gambling Task.

Win condition		Loss condition		Safe condition	
L1	L2	L1	L2	L1	L2
很好	Good	糟糕	Bad	稳妥	Safe
真行	Cool	遗憾	Sorry	-	-
超赞	Great	悲催	Sad	-	-
太棒了	Excellent	真可恶	Damn	-	-
了不起	Wonderful	太惨了	Terrible	-	-

Procedure

Participants played a Gambling task where they had to choose whether to gamble. They completed 240 trials (divided in for blocks of 60 trials each) while in the fMRI scanner. Before beginning, they were told that 10% of their gains would be added to

their monetary reward for participation, and were asked to complete practice trials until familiarization with the procedure was reached.

In each trial, after a fixation cross displayed for 500 ms, the gambling Ace card stimulus appeared for 3500 ms where participants made their choice whether to gamble, followed by a feedback displayed for 2000 ms and a blank screen displayed for 1000-4000 ms (see Figure 1A). Feedbacks were either positive or negative words followed by gain or loss values (e.g., 'Wonderful! +10\$' in case of win, 'Terrible! -3\$' in case of loss). To encourage participants to bet rather than choosing the safe option, we used 10 as the gain value and -3 as the loss value.

To choose the gambling option, participants had to press the leftward key for half of the trials and the rightward key for the remaining half of the trials. Moreover, the order of language stimuli presentation was counterbalanced across participants (L1 feedbacks in the first two blocks vs. L2 feedbacks in the first two blocks).

A. Single Trial **B. Two Trials in a Row**

Figure 1. Panel A displays an example of a trial in the Gambling task, with a L1 feedback (first row) and a L2 feedback (second row). Participants were presented with the winning probability and chose either the ‘gamble’ or the ‘safe’ option. Next, they received a feedback, either positive or negative. Panel B displays two trials in a row where a feedback phase in the first trial and a subsequent choice phase in the second

trial can be indentified.

fMRI Data Acquisition

Functional imaging was performed with a GE Discovery MR750 3T scanner, using a T2*-weighted echo planar imaging (EPI) sequence. Volumes covered the whole brain (repetition time = 2000 ms, echo time = 30 ms, flip angle = 90°, sequential acquisition = 33 axial slices, slice thickness = 3.5 mm, image matrix = 64 × 64, field of view = 224 × 224 mm, voxel size = 3.5 × 3.5 × 4.2 mm). There were four sessions with 255 time points. Structural images were acquired with a T1-weighted 3-D MPRAGE sequence (repetition time = 6.652 ms, echo time = 2.928 ms, flip angle = 12°, sequential acquisition = 192 slices, slice thickness = 1 mm, spacing between slices = 1 mm, image matrix = 256 × 256, field of view = 256 × 256 mm, voxel size = 1 × 1 × 1 mm).

Behavioral Data Analysis

Participants' choices in the Gamling task (0 = safe choice, 1 = bet choice) were analyzed with a generalized linear mixed effect model using feedback (the one received in the trial before: positive, negative) and language (L1, L2) as fixed effects. Risk types, probability of winning and participants were included as random effects.

fMRI Data Preprocessing

fMRI data were preprocessed with DPABI (Yan et al., 2016). First, we converted the EPI DICOM data to NIFTI format, discarding the first five volumes of each run because of T1 relaxation artifacts. Second, images were time-sliced and realigned to the first scan to correct for head motion. Third, structural images were co-registered

with the mean functional images and normalized to the Montreal Neurological Institute (MNI) template. Fourth, all voxels were resampled to $3 \times 3 \times 3$ mm. Fifth, all functional volumes were smoothed by using a 6-mm FWHM isotropic Gaussian kernel.

fMRI Data Statistical Analysis

Whole-brain

The fMRI data were analyzed using SPM12 software. In the first-level analysis, fMRI data were analyzed with a general linear model. Using the presentation of feedback as onset, trials (win, loss, safe) were modeled separately for L1 and L2, resulting in six conditions: L1-Win, L1-Loss, L1-Safe, L2-Win, L2-Loss, L2-Safe. The vectors (onset time of trials in each condition) were convolved with the canonical hemodynamic response function (HRF). Six head motion parameters were included as noise regressors. The least-squares parameter estimates of the height of the best-fitting canonical HRF for each condition were used in pairwise comparisons which resulted in subject-specific contrast images used in the second-level analyses.

In the second-level analysis, we analyzed within- and between-language comparisons in the feedback phase. Within-language comparisons included those for L1 condition (L1-Win vs. L1-Loss; L1-Win vs. L1-Safe; L1-Loss vs. L1-Safe) and those for L2 condition (L2-Win vs. L2-Loss, L2-Win vs. L2-Safe, L2-Loss vs. L2-Safe). Between-language comparisons were L1-Win vs. L2-Win, L1-Loss vs. L2-Loss, and L1-Safe vs. L2-Safe. We next analyzed whether feedbacks influenced the subsequent neural activation in the choice phase (Figure 1b). Family Wise Error (FWE) voxel or cluster correction was applied.

PsychoPhysiological Interaction

PsychoPhysiological Interaction (PPI) analysis was used to elucidate the feedback-dependent functional connectivity in both L1 and L2 (Friston et al. 1996; O'Reilly et al., 2012). Given the key role of prefrontal cortex (PFC) areas in emotion regulation and decision making (Apps & Ramnani, 2017; Asgher et al., 2018; Miller & Cohen, 2001; Nishitani & Shinohara, 2013) and the fact that these regions were activated in both L1 and L2 Loss vs. Safe contrast, the PFC areas activated for Loss > Safe were used as source regions for extracting the eigenvariate of the fMRI signal. For each participant, PPI regressors including the psychophysiological interaction term were calculated and used in the generalized linear model. For the comparisons, contrast images of the PPIs were analyzed using t-test, and only clusters that survived cluster-level correction for multiple comparison ($p_{FWE} < .05$, uncorrected voxel-level $p < .001$) were reported.

Results

Behavioral Results

The analysis on gambling choices revealed a significant main effect of feedback, $\beta = 0.33$, $z = 3.04$, $p = .002$. Participants gambled more after receiving a positive (win) feedback than a negative (loss) feedback. Crucially, there was a significant interaction between language and feedback, $\beta = 0.21$, $z = 0.11$, $p = .035$. In L2 but not in L1 context, participants gambled more after receiving a positive than a negative feedback, $\beta = -0.54$, $z = 0.36$, $p < .001$. Moreover, after a positive feedback, participants gambled more in L2 than in L1 context, $\beta = -0.36$, $z = 0.26$, $p = .009$.

fMRI Results

Whole-brain Analysis of the Feedback Phase

Analyzing between-language comparisons, we found that, compared to L1, L2 elicited greater activation in the parahippocampus during win feedbacks, and greater activation in the bilateral primary visual cortex (V1) during both win and loss feedbacks (see Table 3 and Figure 2).

Table 3

MNI Coordinates of Local Maxima Activated for Between-language Contrasts in the Feedback Phase (FWE Voxel or Cluster Corrected, Uncorrected $p < .005$).

Contrast	Volume	Area of activation	MNI coordinates			t	P_{FWE}
			X	y	z		
Win: L2 > L1	448	R V1	24	-66	15	4.31	< .001
		R Parahippocampus					
	246	L V1 (lingual)	-15	-75	-6	4.36	.013
	191	L V1 (calcarine, cuneus)	-15	-84	21	5.54	.041
Loss: L2 > L1	322	L V1	-9	-87	30	4.54	< .001
		L precuneus					

Note: L = left, R = right.

Figure 2. Between-language comparisons. Panel A displays V1 activation in L2-Win vs. L1-Win contrast. Panel B displays V1 activation in L2-Loss vs. L1-Loss contrast.

Within both L1 and L2 conditions, the Loss > Safe contrasts elicited more activation in the bilateral vmPFC, dmPFC, and bilateral insula. Moreover, the Loss > Safe and Loss > Win contrasts in L2 recruited additional dlPFC activity (Table 4 and Figure 3).

Thus, to some extent L1 and L2 activated similar brain regions. However, L2 selectively recruited additional dlPFC activity. Moreover, between-language contrasts revealed that, compared to L1, L2 activated more attention and memory areas (parahippocampus and bilateral V1) when processing both win and loss feedbacks.

Table 4

MNI Coordinates of Local Maxima Activated for Within-language Contrasts in the Feedback Phase (FWE Cluster Corrected, Uncorrected Threshold $p < .001$).

Contrast	Volume	Area of activation	MNI coordinates			t	P_{FWE}
			X	y	z		
L1: Win > Loss	-	-					
L1: Loss > Win	-	-					
L1: Win > Safe	264	L V1	-15	-102	-6	5.85	< .001
	405	R V1	18	-90	-3	7.87	< .001
	102	Corpus Callosum					.013
L1: Loss > Safe	161	R vmPFC	24	27	-9	5.85	.001
		R insula					
	153	L vmPFC	-36	24	0	4.97	.001
		L insula					
	114	L middle occipital gyrus	-39	-81	-18		.006
	205	R middle occipital gyrus	27	-96	-6		< .001
	264	dmPFC	3	39	33	6.23	< .001
L2: Win > Loss	134	R V1	15	-75	6	5.91	.004
	86	L V1	-12	-81	-6	5.07	.030
L2: Loss > Win	98	L dlPFC	-42	21	6	5.26	.018
		L vmPFC					
	202	L & R SMA	0	18	54	6.1	< .001
L2: Win > Safe	311	L & R V1	-12	-81	6	5.45	< .001
L2: Loss > Safe	244	L middle occipital gyrus	-48	-66	27	6.57	< .001
		L fusiform					
	110	R insula	27	24	-6	5.06	.006
	226	L vmPFC	-27	21	0	5.22	< .001
		L dlPFC					
	177	R vmPFC	48	30	15	5.47	< .001
		R dlPFC					
	278	L & R dmPFC	9	21	57	6.51	< .001

Note: L = left, R = right, SMA= supplementary motor cortex.

Figure 3. Within-language comparisons. Panels A1-2 display V1 areas activation in Win > Safe contrasts for L1 and L2. Panels B1-2 display activated areas in Loss > Safe

contrasts for L1 and L2 (dmPFC and bilateral insula for both languages, dlPFC for L2).

Analyzing the influence of feedbacks on the neural activation in the choice phase, we found that hippocampus activated more in the choice phase after a L2 positive win feedback than a L2 safe feedback (see Table 5 and Figure 4).

Table 5

MNI Coordinates of Local Maxima Activated for Within-language Contrasts in the Choice Phase (FWE Voxel Corrected, Uncorrected Threshold $p < .001$).

Contrast	Volume	Area of activation	MNI coordinates			t	P_{FWE}
			X	y	z		
L2: Win > Safe	52	R Hippocampus	36	-27	-9	7.34	.018

Figure 4. Right hippocampus activation in the choice phase after a win feedback.

PsychoPhysiological Interaction Results

We found that the feedback-functional connectivity of the dmPFC (source region)

with the right dlPFC and the left inferior parietal lobule IPL was significantly stronger while participants processed L1 loss feedbacks than L1 safe feedbacks (see Table 6 and Figure 5). Instead, in L2 context, the connectivity between right dlPFC and bilateral middle occipital gyrus (MOC) was significantly stronger for loss than safe feedbacks.

Table 6

MNI Coordinates of Local Maxima Activated for PPIs at the Feedback Phase for Loss > Safe Contrast (FWE Voxel or Cluster Corrected $p < .001$).

Source region	Language	Volume	Area of connectivity	MNI coordinates			t	P_{FWE}
				x	y	z		
dmPFC	L1	63	R dlPFC	33	15	30	7.21	.028
		61	L Inferior Parietal Lobule	-51	-30	36	6.32	.032
R dlPFC	L2	78	L Middle Occipital Gyrus	-39	-72	9	4.98	.015
		214	R Middle Occipital Gyrus	42	-72	3	6.91	<.001

Figure 5. PPI results for Loss > Safe contrast in L1 and L2. Panel A shows regions significantly connected with the dmPFC in the L1 context. Panel B shows regions significantly connected with the dlPFC in the L2 context.

Correlations between Gambling Rates and Brain Activity

We calculated the correlations between gambling rates in both L1 and L2 conditions and brain areas activation in the feedback phase associated to within-language contrasts.

The whole-brain activated areas in those contrasts and in the functional connectivity analysis were extracted as ROIs and used here. A FDR correction ($q = .05$; Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001) was applied to p values which are reported as corrected. See Appendix 1 for the full results.

Gambling ratio in L1 was negatively correlated with the activation of dmPFC in Loss > Safe contrast, $r = -.74$, $p = .016$ (Figure 6A). In L1 context, participants who gambled more also experienced lower dmPFC activation while receiving a loss negative feedback than a safe neutral feedback. Gambling ratio in L2 was instead negatively correlated with the right dlPFC activation in the Loss > Safe contrast, $r = -.70$, $p = .020$ (Figure 6B). In L2 context, participants who gambled more also experienced less dlPFC activation while receiving a loss feedback than a safe feedback. No significant correlation was found between the gambling ratio and the strength of the functional connectivity in both L1 and L2 contexts.

A. The dmPFC activation in *L1 Loss > L1 Safe* contrast

B. The dlPFC activation in *L2 Loss > L2 Safe* contrast

Figure 6. Correlations between gambling rates and brain activity in the feedback phase.

Panel A shows a negative correlation between gambling ratio and dmPFC activation in the *L1-Loss > L1-Safe* contrast. Panel B shows a negative correlation between gambling ratio and dlPFC activation in *L2-Loss > L2-Safe* contrast.

Discussion

The present study aimed at elucidating the neural substrates of the language-related influence of emotion on economic decision making. We found evidence that, overall, emotions were processed differently in the two languages, and that these different accesses to emotion had an influence on participants' decision making.

Indeed, in the feedback phase, access to emotion in L2 was different to access to emotion in L1. While it is true that across languages similar reward-related emotion areas were activated (insula, vmPFC, and dmPFC), only the processing of L2 words activated more dlPFC and was associated to a significant functional connectivity between dlPFC and visual cortex in the Loss vs. Safe contrast. Moreover, only the processing of L1 words enhanced the connectivity between dmPFC and left IPL. Correlational analyses too shed light on the language-related differences in access to emotion. We found a correlation between gambling rates and dmPFC activation in the L1-Loss > L1-Safe contrast but a correlation between gambling rates and dlPFC in the L2-Loss > L2-Safe contrast. Given the central role of dlPFC in disengaging attention, the processing of negative emotion in L2 may be mediated by attention control whereas in L1 may instead be linked to areas relevant to emotion regulation.

Next, we found evidence that after having received a positive rather than a neutral feedback in L2, hippocampus was more activated during decision making. This was true for L2 but not for L1, and together with the other results it suggests that in the L2 context the disengaging from negative emotions combined with the increasing of memory and attentional processing for positive stimuli and emotions results in a

positive bias in emotional processing that eventually influences bilinguals' decisions.

The dmPFC and dlPFC Role in Mediating Decision Making in L1 and L2

We have seen that during the processing of L2 words (in the Loss vs. Safe contrast), more dlPFC activation was observed as well as greater functional connectivity between the dlPFC and visual cortex. By contrast, in L1 context greater functional connectivity was observed between dmPFC and left IPL. Correlation results too indicated that emotional process and decision making are linked to dmPFC in L1 and dlPFC in L2.

The medial PFC has been shown to be closely connected with subcortical limbic structures (Miller & Cohen, 2001), a plausible zone of interaction between emotion processing and high-level cognitive processing. Meta-analysis work revealed that mPFC is often activated in emotional tasks, and dmPFC in particular along with the anterior cingulate cortex (ACC) is involved in emotion processing such as emotion regulation, appraisal of emotions, and emotion-driven decision making (Apps & Ramnani, 2017; Dörfel et al., 2014; van Holstein & Floresco, 2019). Moreover, it has shown that dmPFC activity can predict people's impulsivity in decision making (Christopoulos et al., 2009; Lv et al., 2019; Vorobyev et al., 2015; Xue et al., 2010).

The other area that played a crucial role in L1 context was the IPL. This area is known to be implicated in numeric representation, uncertainty and feedbacks processing in decision making tasks, and it has been shown to be more activated during risky than conservative decision making (Miles et al., 2004; Vickery & Jiang, 2009; Zhang et al., 2017). Here, the enhanced connectivity between dmPFC and IPL in the Loss vs. Safe contrast and the negative correlation between gambling rates and dmPFC

activation for negative vs. neutral feedbacks may indicate that in L1 context dmPFC integrated uncertainty and negative emotion leading participants to control the impulse to gamble especially after a negative loss feedback.

A different scenario characterized bilinguals' neural responses in L2 context. First, dlPFC activation in Loss vs. Safe contrast was negatively correlated with gambling rates. The dlPFC has been found to be involved in cognitive control processes (such as selective attention, task and language switching; Abutalebi et al., 2013; Blanco-Elorrieta & Pylkkänen, 2018; Branzi et al., 2016) and abstract reasoning (e.g., cost-benefit analysis; Trémolière et al., 2018). It influences decision making and modulates emotional states via top-down attentional control (Asgher et al., 2018; Chung et al., 2019; De Raedt et al., 2015; Sanchez et al., 2016). So, for instance, the failure to disengage attention from negative feelings is bound to dlPFC dysfunction (De Raedt & Koster, 2010). Moreover, by experimentally manipulating the right dlPFC activation, researchers were able to uncover the causal relationship between this area and the attentional processing on emotion information (Kluger & Triggs, 2007; Molavi et al., 2020; Nitsche et al., 2008; Sanchez et al., 2016; Sanchez-Lopez et al., 2018). The dlPFC has thus been shown to be involved in the top-down attentional control and can modulate decision making by divert attention from negative stimuli. Here, we suggest that dlPFC regulated gambling behavior and reduced impulsivity in L2 context by enhancing inhibitory control over the processing of negative stimuli.

Second, we observed greater connectivity between dlPFC and visual cortex (bilateral middle occipital gyrus) in the L2 Loss vs. Safe contrast. This connectivity

may indicate that additional cognitive resources were used in L2 context to divert the attention from the negative stimuli and emotions. This would be in line with the protective mechanism hypothesis put forward by Wu and Thierry (2012) and discussed in the introductory section. The full process of L2 negative words may have been inhibited, as evidenced by the involvement of brain areas responsible for language and cognitive control.

Positive Bias in L2 Context

Behavioral results revealed that after a positive feedback bilinguals gambled more in L2 than in L1 context. Moreover, we observed greater hippocampus activity after a positive win feedback rather than a neutral feedback in L2 but not in L1. The hippocampus is known for its role in declarative memory (Eichenbaum, 2004; Ramirez et al., 2014). It is also implicated in the manifestation of emotionality and it has been shown to be implicated in the modulation of depression-related behaviors (Zhang et al., 2019). Here, then, a possibility is that L2 positive feedbacks received more attention and a deeper processing, as evidenced by the hippocampus activity. This bias toward positive stimuli may have favored a positive emotional state and in turn influenced decision making. The whole-brain results in the feedback phase are consistent with this possibility: L2 feedbacks processing was associated with increased visual cortex activation where visual cortex activation is thought to be related to attentional engagement (Bradley et al., 2003; Chen et al. 2015; Keil et al., 2009).

Several studies reported that the visual cortex activation is linked to the processing of emotional information (Bekhtereva et al., 2015; Chen et al., 2015; Herbert, 2009;

Frank et al., 2019; Keil et al., 2009; Sambuco et al., 2020; Schindler & Kissler, 2016; Trauer et al., 2019). A possibility is that emotionality is modulated by the anterior cortex and subcortical structures that send their modulation back to the visual cortex through the afferent pathway, resulting in an enhanced attentional engagement in the visual cortex (Keil et al., 2009). It was indeed reported evidence of stronger re-entrant connections to the visual cortex when stimuli were emotionally arousing rather than neutral (Keil et al., 2009). Thus, here too for the L2 context it might be that the increased involvement of the visual cortex was driven by re-entrant modulation resulting in more attentional engagement to positive feedbacks.

In addition, we found that while processing win feedbacks in L2 but not in L1, the parahippocampus (the main source of cortical input to the hippocampus), along with the visual cortex, activated too. There is evidence that a variety of information from other areas is funneled into the hippocampus via the parahippocampal region (Eichenbaum, 2006; Rolls, 2018). Here, a possibility is that positive L2 information was directed to the hippocampus through the parahippocampal path, receiving a deeper processing in the working memory. Positive L2 words may have received enhanced attention in the visual cortex and may have been further processed by the hippocampus thus affecting the emotional state of participants and their decision making.

By contrast, the right dlPFC helped participants to divert their attention from negative L2 words. While in L1 context the dmPFC activation may have been linked to loss or risk aversion as described in prior studies (e.g., Monosov, 2017), in L2 context loss aversion was mediated by the dlPFC, an area related to language control and

attentional disengagement. Bilinguals may have been more likely to divert their attention from negative words in L2 than in L1, and coupled with an enhanced tendency to experience positive feelings after a positive feedback, this resulted in an overall reduction of loss aversion in L2. The neural activation pattern we found can thus help better characterizing the effect of foreign language in reducing loss aversion found in many studies (Corey et al., 2017; Costa et al., 2014; Keysar et al., 2012).

Evidence of deep processing of positive words and disengagement from negative emotions in L2 context is consistent with the positive bias hypothesis and its protective mechanism version discussed in the Introduction: In L2, bilinguals tend to focus on positive emotions and stimuli and avoid negative emotional states. By contrast, the embodiment approach can account for the reduced negative emotionality but not for the positivity bias. Within this approach, the difference in emotionality between L1 and L2 is explained by the fact that L1 acquisition is highly contextual where affective words are closely associated with emotional feelings, whereas L2 is mostly acquired in decontextualized settings (Caldwell-Harris, 2014; Pavlenko, 2012; Sheikh & Titone, 2015). A possibility to reconcile this view with our results is to observe that in decontextualized or emotionally neutral contexts people may tend to pay more attention to positive feelings and stimuli.

Conclusion

In this study, we provided evidence that emotionally valenced words were processed differently depending on whether they were presented in native L1 language or foreign L2 language. In particular, we showed that distinct brain activation patterns

were associated with the processing of emotionally valenced stimuli and with the influence of emotion on decision making in L1 and in L2.

While in L1 context the processing of negative words was linked to dmPFC activation, in L2 context it was mediated by the activation of dlPFC, an area known to be associated with attentional disengagement from negative stimuli. Moreover, compared to L1 context, L2 context enhanced bilinguals' willingness to gamble after a positive feedback. Further clarifying the positivity bias in L2 words processing and decision making, we found enhanced hippocampus activity during decision making after a positive rather than a neutral feedback, suggesting that additional attention and declarative memory resources were in place for positive information. Finding that in L2 context positive feedbacks processing and dlPFC's modulation of negatively valenced stimuli were enhanced is consistent with views positing that L2 leads people to focus more on positive information and less on negative ones. More in general, these findings help elucidating the neural bases underpinning the interaction between language and emotion.

References

- Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex*, 49, 905-911.
<https://doi.org/10.1016/j.cortex.2012.08.018>
- Allan, D. (2004). *Oxford placement test 2: Test pack*. Oxford, England: Oxford University Press. <https://doi.org/10.1093/cercor/bhx183>
- Apps, M. A. J., & Ramnani, N. (2017). Contributions of the medial prefrontal cortex to social influence in economic decision-making. *Cerebral Cortex*, 27, 1-14.
<https://doi.org/10.1093/cercor/bhx183>
- Asgher, U., Ahmad, R., Ayaz, Y., Naseer, N., Ali, L., Ruiz, J. A., & Kole, M. (2017, July). Analyzing various functions of prefrontal cortex (PFC) in decision making via brain imaging techniques. Paper presented at the International Conference on Applied Human Factors and Ergonomics. https://doi.org/10.1007/978-3-319-60747-4_23
- Baumeister, J. C., Foroni, F., Conrad, M., Rumiati, R., & Winkielman P. (2017). Embodiment and emotional memory in first vs. second language. *Frontiers in Psychology*, 8, 394. <https://doi.org/10.3389/fpsyg.2017.00394>
- Bekhtereva, V., Craddock, M., & Müller, M. M. (2015). Attentional bias to affective faces and complex IAPS images in early visual cortex follows emotional cue extraction. *NeuroImage*, 112, 254-266.
<https://doi.org/10.1016/j.neuroimage.2015.03.052>

- Blanco-Elorrieta, E., Emmorey, K., & Pykkänen, L. (2018). Language switching decomposed through MEG and evidence from bimodal bilinguals. *Proceedings of the National Academy of Sciences of the USA*, 115, 9708-9713. <https://doi.org/10.1073/pnas.1809779115>
- Blanco-Elorrieta, E., & Pykkänen, L. (2018). Ecological validity in bilingualism research and the bilingual advantage. *Trends in Cognitive Sciences*, 22, 1117-1126. <https://doi.org/10.1016/j.tics.2018.10.001>
- Bradley, M. M., Sabatinelli, D., Lang, P. J., Fitzsimmons, J. R., King, W., & Desai, P. (2003). Activation of the visual cortex in motivated attention. *Behavioral Neuroscience*, 117, 369-380. <https://doi.org/10.1037/0735-7044.117.2.369>
- Branzi, F. M., Della Rosa, P. A., Canini, M., Costa, A., & Abutalebi, J. (2016). Language control in bilinguals: monitoring and response selection. *Cerebral Cortex*, 26, 2367-2380. <https://doi.org/10.1093/cercor/bhv052>
- Caldwell-Harris, C. L. (2014). Emotionality differences between a native and foreign language: theoretical implications. *Frontiers in psychology*, 5, 1055. <https://doi.org/10.3389/fpsyg.2014.01055>
- Caldwell-Harris, C., Kronrod, A., & Yang, J. (2013). Do more, say less: Saying “I love you” in Chinese and American cultures. *Intercultural Pragmatics*, 10, 41-69. <https://doi.org/10.1515/ip-2013-0002>
- Caldwell-Harris, C. L., Tong, J., Lung, W., & Poo, S. (2011). Physiological reactivity to emotional phrases in Mandarin—English bilinguals. *International Journal of Bilingualism*, 15, 329-352. <https://doi.org/10.1177/1367006910379262>

- Chen, P., Lin, J., Chen, B., Lu, C., & Guo, T. (2015). Processing emotional words in two languages with one brain: ERP and fMRI evidence from Chinese–English bilinguals. *Cortex*, 71, 34-48. <https://doi.org/10.1016/j.cortex.2015.06.002>
- Cheng, M., Setoh, P., Bornstein, M. H., & Esposito, G. (2020). She thinks in English, but she wants in Mandarin: Differences in Singaporean bilingual English–Mandarin maternal mental-state-talk. *Behavioral Sciences*, 10, 106. <https://doi.org/10.3390/bs10070106>
- Christopoulos, G. I., Tobler, P. N., Bossaerts, P., Dolan, R. J., & Schultz, W. (2009). Neural correlates of value, risk, and risk aversion contributing to decision making under risk. *The Journal of Neuroscience*, 29, 12574-12583. <https://doi.org/10.1523/JNEUROSCI.2614-09.2009>
- Chung, Y. S., Poppe, A., Novotny, S., Epperson, C. N., Kober, H., Granger, D. A., ... & Stevens, M. C. (2019). A preliminary study of association between adolescent estradiol level and dorsolateral prefrontal cortex activity during emotion regulation. *Psychoneuroendocrinology*, 109, 104398. <https://doi.org/10.1016/j.psyneuen.2019.104398>
- Coltheart, M. (1981). The MRC psycholinguistic database. *The Quarterly Journal of Experimental Psychology*, 33, 497-505. <https://doi.org/10.1080/14640748108400805>
- Corey, J. D., Hayakawa, S., Foucart, A., Aparici, M., Botella, J., Costa, A., & Keysar, B. (2017). Our moral choices are foreign to us. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43, 1109-1128.

<https://doi.org/10.1037/xlm0000356>

Eichenbaum, H. (2004). Hippocampus: cognitive processes and neural representations that underlie declarative memory. *Neuron*, 44, 109-120.

<https://doi.org/10.1016/j.neuron.2004.08.028>

Herbert, C., Ethofer, T., Anders, S., Junghofer, M., Wildgruber, D., Grodd, W., & Kissler, J. (2009). Amygdala activation during reading of emotional adjectives—an advantage for pleasant content. *Social Cognitive and Affective Neuroscience*, 4, 35-49. <https://doi.org/10.1093/scan/nsn027>

Costa, A., Foucart, A., Arnon, I., Aparici, M., & Apesteguia, J. (2014). “Piensa” twice: On the foreign language effect in decision making. *Cognition*, 130, 236-254.

<https://doi.org/10.1016/j.cognition.2013.11.010>

Cox, J. G., & Zlupko, G. M. (2019). Individual differences in language experience and bilingual autobiographical memory. *International Journal of Bilingualism*, 23, 1180-1194. <https://doi.org/10.1177/1367006917728394>

De Raedt, R., & Koster, E. H. W. (2010). Understanding vulnerability for depression from a cognitive neuroscience perspective: A reappraisal of attentional factors and a new conceptual framework. *Cognitive, Affective, & Behavioral Neuroscience*, 10, 50-70. <https://doi.org/10.3758/s13415-018-0582-8>

De Raedt, R., Vanderhasselt, M-A., & Baeken, C. (2015). Neurostimulation as an intervention for treatment resistant depression: From research on mechanisms towards targeted neurocognitive strategies. *Clinical Psychology Review*, 41, 61-69.

<https://doi.org/10.1016/j.cpr.2014.10.006>

Dewaele, J-M., & Costa, B. (2013). Multilingual clients' experience of psychotherapy.

Language and Psychoanalysis, 2, 31-50.

Dörfel, D., Lamke, J. P., Hummel, F., Wagner, U., Erk, S., & Walter, H. (2014).

Common and differential neural networks of emotion regulation by detachment, reinterpretation, distraction, and expressive suppression: a comparative fMRI investigation. *NeuroImage*, 101, 298-309.

<https://doi.org/10.1016/j.neuroimage.2014.06.051>

Dudschig, C., de la Vega, I., & Kaup, B. (2014). Embodiment and second-language:

Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm. *Brain & Language*, 132, 14-21. <https://doi.org/10.1016/j.bandl.2014.02.002>

Eichenbaum, H. (2007). Comparative cognition, hippocampal function, and recollection. *Comparative Cognition & Behavior Reviews*, 2, 47-66.

<https://doi.org/10.3819/ccbr.2008.20003>

El-Dakhs, D. A. S., & Altarriba, J. (2018). The distinctiveness of emotion words: does

it hold for foreign language learners? The case of Arab EFL learners. *Journal of Psycholinguistic Research*, 47, 1133-1149. <https://doi.org/10.1007/s10936-018-9583-6>

El-Dakhs, D. A. S., & Altarriba, J. (2019). How do emotion word type and valence

influence language processing? The case of Arabic–English bilinguals. *Journal of Psycholinguistic Research*, 48, 1063-1085. <https://doi.org/10.1007/s10936-019-09647-w>

- Fan, L., Xu, Q., Wang, X., Zhang, F., Yang, Y., & Liu, X. (2016). Neural correlates of task-irrelevant first and second language emotion words – evidence from the emotional face–word Stroop task. *Frontiers in Psychology*, 7, 1672. <https://doi.org/10.3389/fpsyg.2016.01672>
- Foroni, F. (2015). Do we embody second language? Evidence for ‘partial’ simulation during processing of a second language. *Brain and Cognition*, 99, 8-16. <https://doi.org/10.1016/j.bandc.2015.06.006>
- Frank, D. W., Costa, V. D., Averbeck, B. B., & Sabatinelli, D. (2019). Directional interconnectivity of the human amygdala, fusiform gyrus, and orbitofrontal cortex in emotional scene perception. *Journal of Neurophysiology*, 122, 1530-1537. <https://doi.org/10.1152/jn.00780.2018>
- Gao, S., Zika, O., Rogers, R. D., & Thierry, G. (2015). Second language feedback abolishes the “Hot Hand” effect during even-probability gambling. *The Journal of Neuroscience*, 35, 5983-5989. <https://doi.org/10.1523/JNEUROSCI.3622-14.2015>
- Geipel, J., Hadjichristidis, C., & Surian, L. (2015a). The foreign language effect on moral judgment: the role of emotions and norms. *Plos One*, 10, e0131529. <https://doi.org/10.1371/journal.pone.0131529>
- Geipel, J., Hadjichristidis, C., & Surian, L. (2015b). How foreign language shapes moral judgment. *Journal of Experimental Social Psychology*, 59, 8-17. <https://doi.org/10.1016/j.jesp.2015.02.001>
- Geipel, J., Hadjichristidis, C., & Surian, L. (2016). Foreign language affects the contribution of intentions and outcomes to moral judgment. *Cognition*, 154, 34-39.

<https://doi.org/10.1016/j.cognition.2016.05.010>

Iacozza, S., Costa, A., & Duñabeitia, J. A. (2017). What do your eyes reveal about your foreign language? Reading emotional sentences in a native and foreign language.

Plos One, 12, e0186027. <https://doi.org/10.1371/journal.pone.0186027>

Ivaz, L., Costa, A., & Duñabeitia, J. A. (2016). The emotional impact of being myself: Emotions and foreign-language processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 42, 489-496.

<https://doi.org/10.1037/xlm0000179>

Jay, T., Caldwell-Harris, C., & King, K. (2008). Recalling taboo and nontaboo words. *The American Journal of Psychology*, 121, 83-103.

<https://doi.org/10.2307/20445445>

Jończyk, R., Boutonnet, B., Musiał, K., Hoemann, K., & Thierry, G. (2016). The bilingual brain turns a blind eye to negative statements in the second language. *Cognitive, Affective, & Behavioral Neuroscience*, 16, 527-540.

<https://doi.org/10.3758/s13415-016-0411-x>

Keil, A., Sabatinelli, D., Ding, M., Lang, P. J., Ihssen, N., & Heim, S. (2009). Re-entrant projections modulate visual cortex in affective perception: evidence from Granger causality analysis. *Human Brain Mapping*, 30, 532-540.

<https://doi.org/10.1002/hbm.20521>

Keysar, B., Hayakawa, S. L., & An, S. G. (2012). The foreign-language effect: Thinking in a foreign tongue reduces decision biases. *Psychological Science*, 23, 661-668.

<https://doi.org/10.1177/0956797611432178>

- Kluger, B. M., & Triggs, W. J. (2007). Use of transcranial magnetic stimulation to influence behavior. *Current Neurology and Neuroscience Reports*, 7, 491-497.
<https://doi.org/10.1007/s11910-007-0076-5>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, 82.
<https://doi.org/10.18637/jss.v082.i13>
- Liu, L., Margoni, F., He, Y., & Liu, H. (2020). Neural substrates of the interplay between cognitive loading and emotional involvement in bilingual decision making. Pre-print retrieved from <https://doi.org/10.31234/osf.io/jfchd>
- Lv, C., Wang, Q., Chen, C., Qiu, J., Xue, G., & He, Q. (2019). The regional homogeneity patterns of the dorsal medial prefrontal cortex predict individual differences in decision impulsivity. *NeuroImage*, 200, 556-561.
<https://doi.org/10.1016/j.neuroimage.2019.07.015>
- Matsumoto, A., & Stanny, C. (2006). Language-dependent access to autobiographical memory in Japanese-English bilinguals and US monolinguals. *Memory*, 14, 378-390. <https://doi.org/10.1080/09658210500365763>
- Miles, S., Nancy, K., & Neuron, J. (2004). Numerical magnitude in the human parietal lobe; tests of representational generality and domain specificity. *Neuron*, 44, 557-569. <https://doi.org/10.1016/j.neuron.2004.10.008>
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167-202.
<https://doi.org/10.1146/annurev.neuro.24.1.167>

- Molavi, P., Aziziaran, S., Basharpour, S., Atadokht, A., Nitsche, M. A., & Salehinejad, M. A. (2020). Repeated transcranial direct current stimulation of dorsolateral-prefrontal cortex improves executive functions, cognitive reappraisal emotion regulation, and control over emotional processing in borderline personality disorder: a randomized, sham-controlled, parallel-group study. *Journal of Affective Disorders*, 274, 93-102. <https://doi.org/10.1016/j.jad.2020.05.007>
- Monosov, I. E. (2017). Anterior cingulate is a source of valence-specific information about value and uncertainty. *Nature Communications*, 8, 134. <https://doi.org/10.1038/s41467-017-00072-y>
- Nishitani, S., & Shinohara, K. (2013). NIRS as a tool for assaying emotional function in the prefrontal cortex. *Frontiers in Human Neuroscience*, 7, 770. <https://doi.org/10.3389/fnhum.2013.00770>
- Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., ... & Pascual-Leone, A. (2008). Transcranial direct current stimulation: state of the art. *Brain Stimulation*, 1, 206-223. <https://doi.org/10.1016/j.brs.2008.06.004>
- Opitz, B., & Degner, J. (2012). Emotionality in a second language: it's a matter of time. *Neuropsychologia*, 50, 1961-1967. <https://doi.org/10.1016/j.neuropsychologia.2012.04.021>
- O'Reilly, J. X., Woolrich, M. W., Behrens, T. E., Smith, S. M., & Johansen-Berg, H. (2012). Tools of the trade: psychophysiological interactions and functional connectivity. *Social Cognitive and Affective Neuroscience*, 7, 604-609. <https://doi.org/10.1093/scan/nss055>

Pavlenko, A. (2012). Affective processing in bilingual speakers: disembodied cognition?

International Journal of Psychology, 47, 405-428.

<https://doi.org/10.1080/00207594.2012.743665>

Ramirez, S., Tonegawa, S., & Liu, X. (2014). Identification and optogenetic manipulation of memory engrams in the hippocampus. *Frontiers in Behavioral Neuroscience*, 7, 226.

<https://doi.org/10.3389/fnbeh.2013.00226>

Rolls, E. T. (2018). The storage and recall of memories in the hippocampo-cortical system. *Cell and Tissue Research*, 373, 577-604.

<https://doi.org/10.1007/s00441-017-2744-3>

Sambuco, N., Bradley, M., Herring, D., Hillbrandt, K., & Lang, P. J. (2020).

Transdiagnostic trauma severity in anxiety and mood disorders: Functional brain activity during emotional scene processing. *Psychophysiology*, 57, e13349.

<https://doi.org/10.1111/psyp.13349>

Sanchez-Lopez, A., Vanderhasselt, M-A., Allaert, J., Baeken, C., & De Raedt, R. (2018).

Neurocognitive mechanisms behind emotional attention: Inverse effects of anodal tDCS over the left and right DLPFC on gaze disengagement from emotional faces.

Cognitive, Affective, & Behavioral Neuroscience, 18, 485-494.

<https://doi.org/10.3758/s13415-018-0582-8>

Sanchez, A., Vanderhasselt, M-A., Baeken, C., & De Raedt, R. (2016). Effects of tDCS over the right DLPFC on attentional disengagement from positive and negative

faces: An eye-tracking study. *Cognitive, Affective, & Behavioral Neuroscience*, 16,

1027-1038. <https://doi.org/10.3758/s13415-016-0450-3>

- Schindler, S., & Kissler, J. (2016). Selective visual attention to emotional words: Early parallel frontal and visual activations followed by interactive effects in visual cortex. *Human Brain Mapping*, 37, 3575-3587. <https://doi.org/10.1002/hbm.23261>
- Schrauf, R. W., & Rubin, D. C. (2000). Internal languages of retrieval: The bilingual encoding of memories for the personal past. *Memory & Cognition*, 28, 616-623. <https://doi.org/10.3758/BF03201251>
- Sheikh, N. A., & Titone, D. (2015). The embodiment of emotional words in a second language: An eye-movement study. *Cognition & Emotion*, 30, 1-13. <https://doi.org/10.1080/02699931.2015.1018144>
- Sulpizio, S., Toti, M., Del Maschio, N., Costa, A., Fedeli, D., Job, R., & Abutalebi, J. (2019). Are you really cursing? Neural processing of taboo words in native and foreign language. *Brain and Language*, 194, 84-92. <https://doi.org/10.1016/j.bandl.2019.05.003>
- Talmi, D., & Moscovitch, M. (2004). Can semantic relatedness explain the enhancement of memory for emotional words? *Memory & Cognition*, 32, 742-751. <https://doi.org/10.3758/BF03195864>
- Taylor, S. F., Martis, B., Fitzgerald, K. D., Welsh, R. C., Abelson, J. L., Liberzon, I., ... & Gehring, W. J. (2006). Medial frontal cortex activity and loss-related responses to errors. *Journal of Neuroscience*, 26, 4063-4070. <https://doi.org/10.1523/JNEUROSCI.4709-05.2006>
- Trauer, S. M., Müller, M. M., & Kotz, S. A. (2019). Expectation gates neural facilitation of emotional words in early visual areas. *Frontiers in Human Neuroscience*, 13, 281.

<https://doi.org/10.3389/fnhum.2019.00281>

Trémolière, B., Maheux-Caron, V., Lepage, J-F., & Blanchette, I. (2018). TDCS stimulation of the dlPFC selectively moderates the detrimental impact of emotion on analytical reasoning. *Frontiers in Psychology*, 9, 568.

<https://doi.org/10.3389/fpsyg.2018.00568>

van Holstein, M., & Floresco, S. B. (2020). Dissociable roles for the ventral and dorsal medial prefrontal cortex in cue-guided risk/reward decision making. *Neuropsychopharmacology*, 45, 683-693. [https://doi.org/10.1038/s41386-](https://doi.org/10.1038/s41386-019-0557-7)

[019-0557-7](https://doi.org/10.1038/s41386-019-0557-7)

Vickery, T. J., & Jiang, Y. V. (2009). Inferior parietal lobule supports decision making under uncertainty in humans. *Cerebral Cortex*, 19, 916-925.

<https://doi.org/10.1093/cercor/bhn140>

Vidal, A., Costa, A., & Foucart, A. (2019). Are our preferences and evaluations conditioned by the language context? Pre-print retrieved from

<https://doi.org/10.31234/osf.io/by38d>

Vives, M. L., Aparici, M., & Costa, A. (2018). The limits of the foreign language effect on decision-making: the case of the outcome bias and the representativeness heuristic. *PloS one*, 13, e0203528. <https://doi.org/10.1371/journal.pone.0203528>

Vorobyev, V., Kwon, M. S., Moe, D., Parkkola, R., & Hämäläinen, H. (2015). Risk-taking behavior in a computerized driving task: brain activation correlates of decision-making, outcome, and peer influence in male adolescents. *PLoS ONE*, 10,

e0129516. <https://doi.org/10.1371/journal.pone.0129516>

- Vukovic, N., & Shtyrov, Y. (2014). Cortical motor systems are involved in second-language comprehension: evidence from rapid mu-rhythm desynchronisation. *NeuroImage*, 102, 695-703.
<https://doi.org/10.1016/j.neuroimage.2014.08.039>
- Warriner, A. B., Kuperman, V., & Brysbaert, M. (2013). Norms of valence, arousal, and dominance for 13,915 English lemmas. *Behavior Research Methods*, 45, 1191-1207. <https://doi.org/10.3758/s13428-012-0314-x>
- Woumans, E., Van der Cruyssen, I., & Duyck, W. (2020). Crime and punishment: morality judgment in a foreign language. *Journal of Experimental Psychology: General*. Advance online publication. <https://doi.org/10.1037/xge0000736>
- Wu, Y. J., & Thierry, G. (2012). How reading in a second language protects your heart. *The Journal of Neuroscience*, 32, 6485-6489.
<https://doi.org/10.1523/JNEUROSCI.6119-11.2012>
- Xue, G., Lu, Z., Levin, I. P., & Bechara, A. (2010). The impact of prior risk experiences on subsequent risky decision-making: the role of the insula. *NeuroImage*, 50, 709-716. <https://doi.org/10.1016/j.neuroimage.2009.12.097>
- Yan, C. G., Wang, X. D., Zuo, X. N., & Zang, Y. F. (2016). DPABI: Data Processing & Analysis for (Resting-State) Brain Imaging. *Neuroinformatics*, 14, 339-351.
<https://doi.org/10.1007/s12021-016-9299-4>
- Zhang, M., Liu, T., Pelowski, M., Jia, H., & Yu, D. (2017). Social risky decision-making reveals gender differences in the TPJ: A hyperscanning study using functional near-infrared spectroscopy. *Brain and Cognition*, 119, 54-63.

<https://doi.org/10.1016/j.bandc.2017.08.008>

Zhang, T. R., Larosa, A., Raddo, M.-E. D., Wong, V., Wong, A. S., & Wong, T. P. (2019).

Negative memory engrams in the hippocampus enhance the susceptibility to chronic social defeat stress. *The Journal of Neuroscience*, 39, 7576-7590.

<https://doi.org/10.1523/JNEUROSCI.1958-18.2019>

Zheng, L., Mobbs, D., & Yu, R. (2020). The behavioral and neural basis of foreign

language effect on risk-taking. *Neuropsychologia*, 136, e107290.

<https://doi.org/10.1016/j.neuropsychologia.2019.107290>

Appendix 1

Table S1

Correlations Between Activated Brain Areas and Gambling Rates in L1 and L2 Contexts.

Contrasts	ROIs	L1 <i>r</i>	L1 uncorr <i>p</i>	L1 FDR <i>p</i>	L2 <i>r</i>	L2 uncorr <i>p</i>	L2 FDR <i>p</i>
L1 Loss > L1 Safe	dmPFC	-.74	.000	.006	-.42	.067	.207
	L vmPFC	-.23	.328	.537	-.15	.526	.701
	LMOC	-.23	.325	.537	.11	.642	.770
	R vmPFC	-.49	.027	.108	-.27	.247	.445
	R MOC	-.16	.493	.683	.13	.589	.731
L1 Win > L1 Safe	L V1	-.34	.148	.333	-.08	.741	.819
	R V1	-.34	.138	.331	-.14	.565	.726
	dmPFC	-.51	.023	.104	-.47	.036	.130
L2 Loss > L2 Safe	R dlPFC	-.51	.021	.104	-.70	.001	.018
	L dlPFC	-.37	.113	.291	-.28	.239	.445
	L fusiform	-.30	.195	.413	-.61	.005	.060
	L IPL	-.41	.069	.207	-.52	.019	.104
	L vmPFC	-.21	.371	.581	-.08	.751	.819
L2 Loss > L2 Win	L vmPFC	.16	.491	.683	.53	.017	.104
	SMA	.39	.092	.255	.56	.009	.081
L2 Win > L2 Loss	L V1	.10	.672	.780	.004	.985	.985
	R V1	.02	.938	.965	.06	.814	.862
L2 Win > L2 Safe	L & R V1	.29	.213	.426	.17	.472	.683

Note: L = left, R = right, MOC = middle occipital gyrus, IPL = inferior parietal lobe, FDR = FDR (False Discovery Rate) correction