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Emotion regulation elicits cross-linguistically shared and language-specific forms of linguistic distancing

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Cognitively reappraising a stressful experience—reinterpreting the situation to blunt its emotional impact—is effective for regulating negative emotions. English speakers have been shown to engage in *linguistic distancing* when reappraising, spontaneously using words that are more abstract or impersonal. Across two preregistered studies ($N = 299$), we investigated whether such shifts in language use generalize to Spanish, a language proposed to offer unique tools for expressing psychological distance. Bilingual speakers of Spanish and English and a comparison group of English monolinguals transcribed their thoughts in each of their languages while responding naturally to negative images or reappraising them. Reappraisal shifted markers of psychological distance common to both languages (e.g., reduced use of "I"/"yo"), as well as Spanish-specific markers (e.g., greater use of "estar": "to be" for temporary states). Whether these linguistic shifts reflected successful emotion regulation depended on language experience: in exploratory analyses, the common markers were more strongly linked to reduced negative affect for late than early Spanish learners, and one Spanish-specific marker ("estar") also predicted reduced negative affect for early learners. Our findings suggest that people distance their language in both cross-linguistically shared and language-specific ways when regulating their emotions.

Keywords Emotion regulation, Linguistic distancing, Reappraisal, Psychological distance, Language and thought, Spanish

Suppose you are facing a distressing situation: a setback at work, a strained relationship, or a spate of poor health. To cope, you might tell yourself, "Life is difficult right now, but things will get better." In the language of affective science, you are *cognitively reappraising* your situation—thinking about it differently to blunt its emotional impact. A wealth of research has shown that reappraisal is effective for regulating negative emotions, often because it increases *psychological distance* from the source of stress[1]. For example, people report reduced negative affect when they imagine that aversive events are far away, happened long ago, or are unfolding from an observer's perspective[2,3]. Such self-reports are mirrored by physiological and neural indices of reduced emotional arousal[4,5].

The psychological distance elicited by reappraisal is reflected in the language people use when reappraising. In a study by Nook et al.[6], English-speaking adults used fewer first-person singular pronouns (e.g., "I," "me"), fewer present-tense verbs, and more articles (e.g., "the," "a[n]")—among other words implying social or temporal distance—when reappraising negative stimuli than when responding to them naturally. These subtle linguistic shifts were associated with successful emotion regulation: participants who engaged in more *linguistic distancing* when reappraising reported a greater reduction in negative affect. The same association has been observed in English-speaking children and adolescents[7].

Other recent work suggests that linguistic distancing is both a mirror of emotional well-being and a tool for achieving it[8,9]. Avoiding the word "I," for example, is associated with reduced symptoms of depression and anxiety in the laboratory[10] and in real-world therapeutic contexts[11], and people feel better when they intentionally shift their language in this way[6,12]. Therefore, telling oneself "things are bad right now"—as opposed to "I feel bad right now"—not only reflects successful emotion regulation and adaptive health outcomes, but may also give rise to them.

To date, however, research on linguistic distancing in emotion regulation has focused exclusively on speakers of a single language: English. This approach treats English as a "meta-language" for studying psychological

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phenomena and assumes—rather than tests—generalizability to other languages[13]. In the case of linguistic distancing, this assumption may be unwarranted because the lexical and grammatical devices that track psychological distance in English are not universally shared. For example, some languages (e.g., Korean, Russian) lack articles like "the"[14,15] that an English speaker might use to make a stressful situation feel less immediate (e.g., referring to "the divorce" instead of "my divorce").

Other languages have unique ways of expressing psychological distance. Spanish, for example, has two forms of "to be," one for permanent states ("ser") and the other for temporary conditions ("estar"). Using "estar" in place of "ser" can highlight the transience of a negative experience (e.g., "la vida [está/es] difícil" = "life is difficult [now/indefinitely]"), making it loom less large in one's mind. According to a recent proposal by Llabre[16], "estar" serves as a "tool for negotiation" of stressors, as do three other Spanish markers of psychological distance: diminutives (e.g., "perrito," *little dog*), the subjunctive mood (used when referring to fictional entities or speculative ideas[17]), and positive emotion words (reflecting the "positivity bias" of the Spanish lexicon[18]). These markers can be used to express that a stressful situation is not as bad as it seems (e.g., "sólo un dolorcito," *just a little pain*), is not really happening (e.g., "quizás sea una escena de una película"; *maybe it's a scene from a movie*), or will improve (e.g., "todo va a ir bien," *everything is going to be fine*). Llabre suggested that these features of Spanish, which either have no counterpart in English ("estar," diminutives) or are simply used more widely (subjunctive, positive words), might even have downstream benefits for cardiovascular health.

In light of variation in the distancing "toolkits" afforded by different languages, it is important to expand investigation of linguistic distancing in emotion regulation beyond English. Consider a language that includes both English-attested markers of psychological distance (e.g., first-person singular pronouns, articles) and its own unique markers (e.g., "estar" in Spanish). For speakers of such a language, does reappraisal shift one's use of the cross-linguistically shared markers, the language-specific ones, or both? Which set of distance markers is more strongly associated with successful emotion regulation?

We set out to examine these questions across two preregistered studies, using Spanish as a test case. Both studies used a classic emotion regulation paradigm adapted from previous research on linguistic distancing[6]. Bilingual speakers of Spanish and English transcribed their thoughts in each language while responding naturally to negative images (e.g., a car accident, a cemetery) or reappraising them. After writing about each image, participants rated how they were feeling. In Study 1, a comparison group of English monolinguals also completed this task. For both studies, we assessed the effect of reappraisal on self-reported negative affect and linguistic distancing in Spanish and English, as well as whether greater linguistic distancing when reappraising was associated with a greater reduction in negative affect. In Study 1, the bilingual participants were based in the U.S. and many were late Spanish learners. As a result, any similarities in linguistic distancing between Spanish and English could be due to the relatively English-dominant setting and language background of the participants. In Study 2, we ruled out this possibility by testing bilinguals from majority Spanish-speaking countries (Mexico, Chile, and Spain), almost all of whom were early Spanish learners.

Our indices of linguistic distancing included two preregistered composite measures derived from prior empirical work and theorizing. Each measure comprised several linguistic features thought to track psychological distance. One of the measures, previously validated in English[19], includes features also found in Spanish that reflect a focus on the self and the present moment (e.g., first-person singular pronouns, present-tense verbs) or a more abstract, impersonal perspective (e.g., articles, words with > 6 letters)[6]. The other measure was Spanish-specific, consisting of "estar" and the other features proposed by Llabre[16] as useful for reappraising stressors.

We also conducted three sets of exploratory cross-study analyses. First, we assessed the effect of reappraisal on use of the individual linguistic features comprising each composite measure, as in previous studies with English monolinguals[6,7]. Second, we tested whether reappraisal also shifts the use of generic language—statements expressing broad generalizations about categories (e.g., "snakes are gross"), abstract concepts (e.g., "change is inevitable"), or human experience (e.g., "people need each other"). Certain forms of generics (e.g., generic-you: "you take the good with the bad") are used to convey norms in both English and Spanish[9,20] and have been shown to enhance psychological distance when English speakers reflect on lessons learned from negative personal experiences[9]. Therefore, participants in our studies might increase their use of generics when reappraising negative stimuli, and this linguistic shift might in turn predict successful emotion regulation.

Finally, we compared the linguistic signatures of successful emotion regulation in early and late Spanish learners. For bilinguals who acquired one of their languages before the other, emotions often feel less intense when using the second language (L2) than the first (L1)[21]. Self-reports of dampened emotions in L2 are mirrored by weaker physiological responses to emotion-related words[22,23]. In light of this reduced emotional resonance, Spanish-specific distance markers like "estar" may be less strongly associated with successful emotion regulation for late than early Spanish learners. In some cases, however, emotional resonance may be driven more by language proficiency than age of acquisition[24,25]. Therefore, we also explored whether Spanish proficiency moderated any differences between early and late Spanish learners.

Results

For each of our key research questions, we report the results from both studies in turn. Our preregistered analysis plan closely followed Nook et al.[6]. Non-preregistered analyses are marked below as exploratory.

Did reappraisal reduce negative affect?

To assess this question, we first computed each participant's mean negative affect rating by condition (Look vs. Reappraise) and, for bilinguals, by the language in which trials were completed (Spanish vs. English).

Study 1

Preliminary analyses showed that the order of bilinguals' Spanish and English trial blocks did not interact with condition or language (*p*s > 0.2).

Our main analyses compared (a) bilinguals' affect ratings by language and (b) their ratings in each language to the English monolingual group's ratings. For bilinguals, a 2 (condition) × 2 (language) repeated-measures ANOVA yielded only a main effect of condition, $F(1, 69) = 106.60$, $p < 0.001$, $\eta_p^2 = 0.61$, with no main effect of language, $F(1, 69) = 0.03$, $p = 0.86$, $\eta_p^2 < 0.001$, and no interaction, $F(1, 69) = 0.23$, $p = 0.64$, $\eta_p^2 = 0.003$. Bilinguals felt less negative when reappraising than when responding naturally, whether writing in Spanish (Reappraise: $M = 2.65$, $SD = 0.97$; Look: $M = 3.90$, $SD = 1.19$), $t(69) = -9.85$, $p < 0.001$, $d = 1.18$, or in English (Reappraise: $M = 2.64$, $SD = 1.01$; Look: $M = 3.94$, $SD = 1.24$), $t(69) = -8.90$, $p < 0.001$, $d = 1.06$ (see Fig. 1).

To compare affect ratings between bilinguals and monolinguals, we conducted separate 2 (condition) × 2 (group) mixed ANOVAs, using bilinguals' ratings from either the Spanish or English block. These analyses yielded similar results: a main effect of condition (bilinguals using Spanish vs. monolinguals: $F(1, 161) = 177.88$, $p < 0.001$, $\eta_p^2 = 0.53$; bilinguals using English vs. monolinguals: $F(1, 161) = 159.10$, $p < 0.001$, $\eta_p^2 = 0.50$), no main effect of group (*F*s < 0.2, *p*s > 0.7), and a significant interaction ($F(1, 161) = 11.26$, $p < 0.001$, $\eta_p^2 = 0.07$; $F(1, 161) = 11.77$, $p < 0.001$, $\eta_p^2 = 0.07$).

As shown in Fig. 1, reappraisal reduced negative affect more for bilinguals than monolinguals. Exploratory analyses suggested that this difference may have been driven by bilinguals who identified as Hispanic or Latinx, whose baseline negative affect ratings (Look condition: $M = 4.00$, $SD = 1.19$, $n = 47$) were descriptively higher than those of non-Latinx bilinguals and monolinguals ($M = 3.63$, $SD = 1.16$, $n = 116$), $t(161) = 1.84$, $p = 0.07$, $d = 0.32$. For monolinguals, reappraisal also significantly reduced negative affect (Reappraise: $M = 2.86$, $SD = 1.05$; Look: $M = 3.60$, $SD = 1.18$), $t(92) = -8.48$, $p < 0.001$, $d = 0.88$), replicating previous work[6].

Study 2

As all participants were bilingual, we analyzed their affect ratings using a single 2 (condition) × 2 (language) × 2 (order: Spanish or English block first) mixed ANOVA. There was a main effect of condition, $F(1, 134) = 162.34$, $p < 0.001$, $\eta_p^2 = 0.55$, qualified by a three-way interaction, $F(1, 134) = 5.31$, $p = 0.02$, $\eta_p^2 = 0.04$. No other effects were significant (*p*s > 0.4). Exploratory follow-up analyses indicated that reappraisal reduced negative affect more in each language when the English block preceded the Spanish block (*d*s = 1.21–1.45) than the reverse (*d*s = 0.87–0.89).

Importantly, for every pairwise combination of language and block order, reappraisal significantly reduced negative affect (exploratory *t*-tests: *p*s < 0.001), replicating Study 1. Figure 1 shows the effect of reappraisal in each language across both block orders (Spanish-Reappraise: $M = 2.67$, $SD = 0.92$; Spanish-Look: $M = 3.57$, $SD = 1.06$; English-Reappraise: $M = 2.64$, $SD = 0.93$; English-Look: $M = 3.59$, $SD = 1.10$). A cross-study comparison showed that the reappraisal effect was smaller for the non-U.S. bilinguals in Study 2 than the U.S. bilinguals in Study 1 (condition × study interaction: $F(1, 204) = 6.88$, $p = 0.009$, $\eta_p^2 = 0.03$), driven by higher baseline negative affect for the U.S. group (see Fig. 1).

Did reappraisal increase linguistic distancing?

To assess whether participants distanced their language when reappraising, we computed the two composite measures of linguistic distancing described in the Introduction. The English-derived measure[6,19] includes first-person singular pronouns (e.g., "I," "me"), articles (e.g., "the," "a"), present-tense verbs, discrepancy words (e.g., "could," "should"), and words with more than 6 letters. As all of these word classes are found in both English and

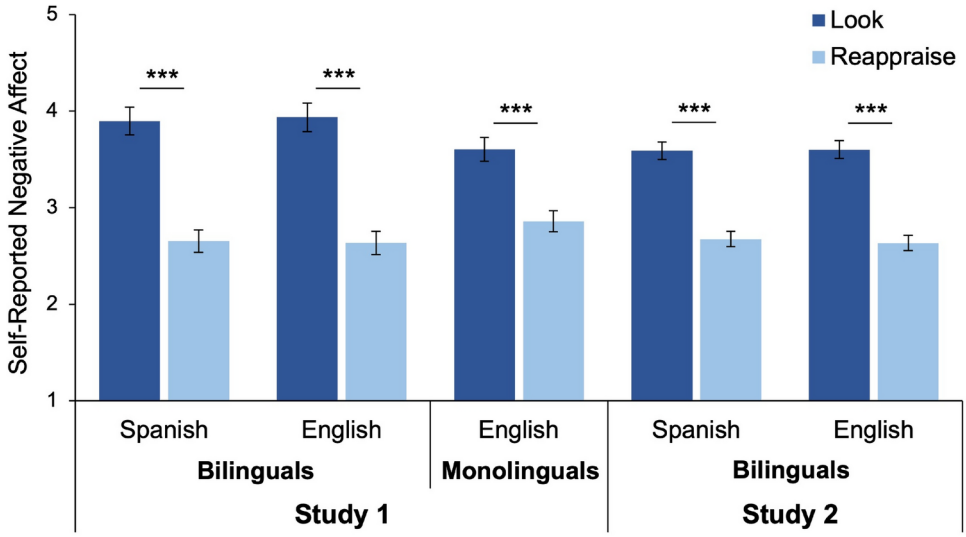

Fig. 1. Mean self-reported negative affect by condition, language, and group. Error bars represent ± SE. ***$p < 0.001$.

Spanish, henceforth we refer to them as "common" (i.e., cross-linguistically shared) markers of psychological distance. Our Spanish-specific measure included the four features of Spanish characterized by Llabre[16] as tools for reappraising stressors: "estar" (and its conjugations), diminutives, subjunctive mood, and positive emotion words.

We used Linguistic Inquiry and Word Count software (LIWC-22)[26] to compute both measures (see Methods). For each, higher scores indicate more distanced language. Markers reflecting *less* distanced language (e.g., first-person singular pronouns) were reverse-scored. We computed each participant's mean standardized score by condition and, for the common markers, by the language in which responses were written.

Study 1

For both composite measures, preliminary analyses indicated that the order of bilinguals' Spanish and English trial blocks did not interact with condition or language ($ps > 0.08$). Therefore, we collapsed across the two orders in subsequent analyses.

For the common markers, a 2 (condition) × 2 (language) repeated-measures ANOVA on bilinguals' composite scores yielded a main effect of condition, $F(1, 69) = 36.75$, $p < 0.001$, $\eta_p^2 = 0.35$, no main effect of language, $F(1, 69) < 0.01$, $p > 0.99$, $\eta_p^2 < 0.001$, and no interaction, $F(1, 69) = 0.91$, $p = 0.34$, $\eta_p^2 = 0.01$. Bilinguals distanced their language when reappraising, whether in Spanish (Reappraise: $M = 0.08$, $SD = 0.31$; Look: $M = -0.08$, $SD = 0.37$), $t(69) = 4.77$, $p < 0.001$, $d = 0.57$, or in English (Reappraise: $M = 0.10$, $SD = 0.31$; Look: $M = -0.10$, $SD = 0.42$), $t(69) = 4.79$, $p < 0.001$, $d = 0.57$ (see Fig. 2).

Between-group comparisons showed that the effect of reappraisal on use of the common markers was similar for bilinguals and English monolinguals. Separate 2 (condition) × 2 (group: bilinguals using Spanish or English vs. monolinguals) mixed ANOVAs each yielded a main effect of condition ($ps < 0.001$), no main effect of group ($ps > 0.99$), and no interaction ($ps > 0.18$). Like bilinguals, monolinguals distanced their language when reappraising (Reappraise: $M = 0.06$, $SD = 0.29$; Look: $M = -0.06$, $SD = 0.40$), $t(92) = 3.74$, $p < 0.001$, $d = 0.39$ (see Fig. 2).

For the Spanish-specific markers, the difference in composite scores between the Reappraise condition ($M = 0.03$, $SD = 0.24$) and the Look condition ($M = -0.03$, $SD = 0.17$) did not reach significance, $t(69) = 1.67$, $p = 0.10$, $d = 0.20$ (see Fig. 3).

Study 2

In Study 1, bilinguals distanced their language in much the same way as English monolinguals when reappraising, with no evidence of Spanish-specific distancing. However, the bilingual sample was arguably English-dominant, as all were U.S.-based and many were late Spanish learners (37% acquired Spanish after age 4). By contrast, Study 2 included bilinguals from majority Spanish-speaking countries, almost all early Spanish learners (99% were L1 Spanish speakers or simultaneous bilinguals). These participants exhibited a somewhat different pattern of linguistic distancing.

For the common markers, a 2 (condition) × 2 (language) × 2 (order of blocks) mixed ANOVA on composite scores yielded a main effect of condition, $F(1, 134) = 25.00$, $p < 0.001$, $\eta_p^2 = 0.16$, qualified by a three-way interaction, $F(1, 134) = 4.46$, $p = 0.04$, $\eta_p^2 = 0.03$. No other effects were significant ($ps > 0.3$). Exploratory follow-up analyses indicated that the effect of reappraisal on use of the common markers was somewhat weaker in

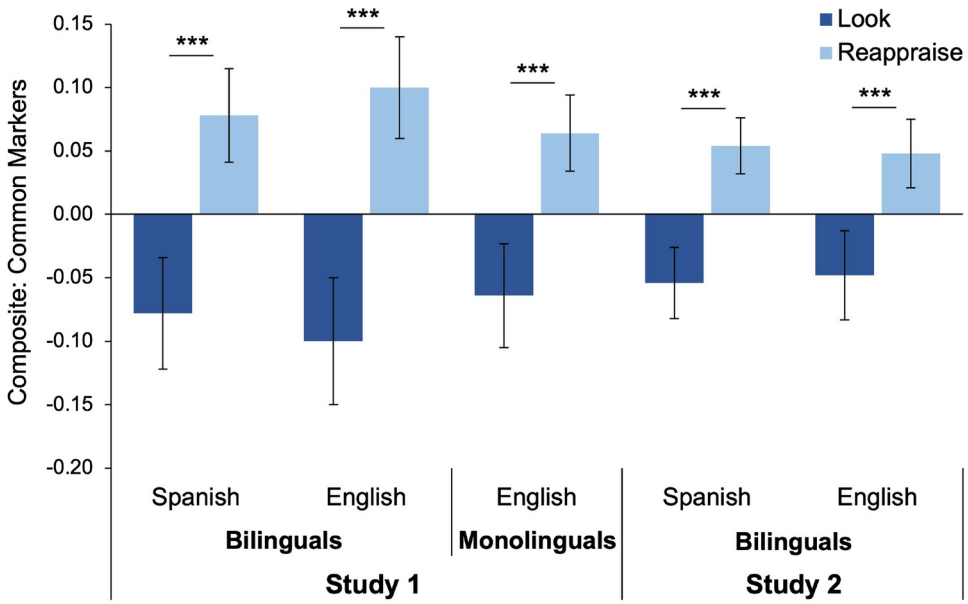

Fig. 2. Mean use of cross-linguistically common distance markers (*z*-scored proportions) by condition, language, and group. Error bars represent ± SE. ***$p < 0.001$.

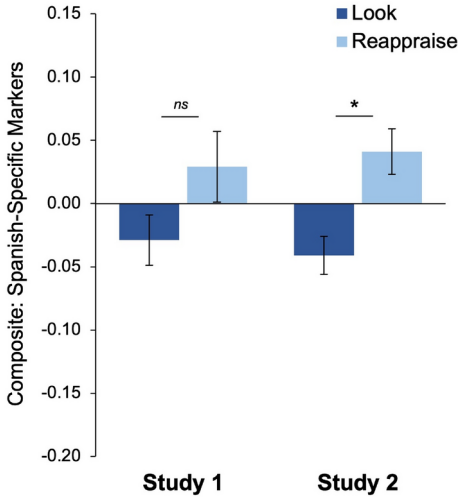

Fig. 3. Mean use of Spanish-specific distance markers (*z*-scored proportions) by condition. Error bars represent ± SE. **p* < 0.05. *ns*, not significant.

	Bilinguals		English monolinguals
	Spanish	English	
Common markers			
First-person singular pronouns	**-0.40**	**-0.38**	**-0.37**
Articles	**0.20**	**0.20**	**0.27**
Present-tense verbs	0.00	**-0.09**	**-0.13**
Discrepancy words	-0.06	-0.04	0.01
Words with > 6 letters	-0.04	-0.06	**-0.12**
Spanish-specific markers			
"Estar"	**0.13**		
Diminutives	0.00		
Subjunctive	-0.02		
Positive emotion words	**0.18**		

Table 1. Mean difference in use of distance markers (Δ: Reappraise—Look; *z*-scored proportions) across Studies 1 and 2 for bilinguals ($n = 206$) and English monolinguals ($n = 93$).

English when the English block came first ($d = 0.25$) than for any other combination of language and block order ($ds = 0.39$–0.43).

Importantly, for every pairwise combination of language and block order, reappraisal significantly increased linguistic distancing (exploratory *t*-tests: $ps < 0.05$), replicating Study 1. Fig. 2 shows the effect of reappraisal in each language across both block orders (Spanish-Reappraise: $M = 0.05$, $SD = 0.26$; Spanish-Look: $M = -0.05$, $SD = 0.33$; English-Reappraise: $M = 0.05$, $SD = 0.32$; English-Look: $M = -0.05$, $SD = 0.40$).

For the Spanish-specific markers, a 2 (condition) × 2 (order of blocks) mixed ANOVA on composite scores yielded only a main effect of condition, $F(1, 134) = 13.62$, $p < 0.001$, $\eta_p^2 = 0.09$ (other effects: $ps > 0.8$). Unlike in Study 1, participants significantly increased their use of Spanish-specific markers when reappraising (Reappraise: $M = 0.04$, $SD = 0.22$; Look: $M = -0.04$, $SD = 0.18$; see Fig. 3).

Exploratory cross-study analyses

Table 1 shows the degree to which reappraisal shifted participants' use of the individual markers comprising the two composite measures, across both studies. When reappraising, bilinguals reduced their use of first-person singular pronouns and increased their use of articles in both languages. They also reduced their use of present-tense verbs in English and increased their use of "estar" and positive emotion words in Spanish ($ps < 0.05$). Use of the other markers did not differ significantly between conditions. The English monolinguals in Study 1 shifted their language in similar ways to the bilinguals in English.

We assessed participants' use of generic language by manually coding each text response (see Methods). For each participant, we computed the proportion of responses containing at least one generic statement (e.g., "los bebés lloran"/"babies cry") in each condition and language. When reappraising, bilinguals reduced their use of generics in Spanish (Reappraise: $M = 0.08$, $SD = 0.12$; Look: $M = 0.12$, $SD = 0.15$), $t(205) = 3.94$, $p < 0.001$, $d = 0.28$, and in English (Reappraise: $M = 0.06$, $SD = 0.10$; Look: $M = 0.08$, $SD = 0.12$), $t(205) = 2.22$, $p = 0.03$,

$d = 0.15$. For the English monolinguals in Study 1, reappraisal did not affect the use of generics (Reappraise: $M = 0.08$, $SD = 0.13$; Look: $M = 0.10$, $SD = 0.16$), $t(92) = 1.46$, $p = 0.15$, $d = 0.15$.

Was increased linguistic distancing when reappraising associated with successful emotion regulation?

To assess whether participants who distanced their language to a greater degree when reappraising were more successful at regulating their emotions, we computed a measure of *reappraisal success*. Following Nook et al.[6], we subtracted each participant's mean negative affect rating in the Reappraise condition from their mean rating in the Look condition, separately for each language. More positive values indicate greater reappraisal success.

We also computed how much each participant distanced their language when reappraising by subtracting their mean score for each composite measure (common or Spanish-specific) in the Look condition from their mean score in the Reappraise condition. More positive values indicate that participants distanced their language more when reappraising than when responding naturally.

As shown in Fig. 4, the two studies yielded different results. In Study 1, bilinguals who relied more on common markers when reappraising in Spanish—but not those who relied more on Spanish-specific markers—had greater reappraisal success (common: $r(68) = 0.48$, $p < 0.001$; Spanish-specific: $r(68) = 0.10$, $p = 0.42$). Greater use of common markers when reappraising in English was also correlated with reappraisal success, replicating previous work[6,7,10], though this correlation only reached significance for English monolinguals (bilinguals using English: $r(68) = 0.22$, $p = 0.06$; monolinguals: $r(91) = 0.22$, $p = 0.03$; see Fig. 4a).

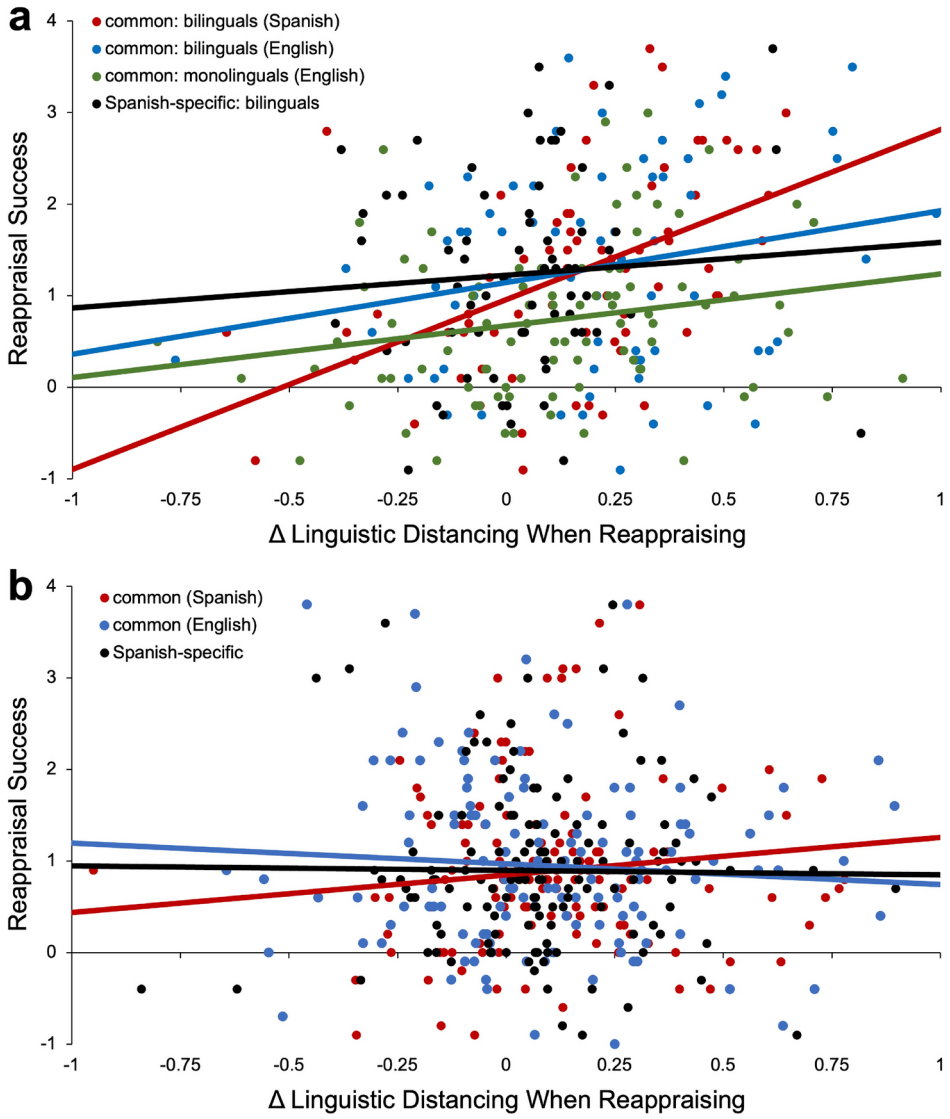

Fig. 4. Relation between the degree to which participants distanced their language (using common or Spanish-specific markers) when reappraising in Spanish or English (*x*-axis) and reappraisal success (the degree to which negative affect was reduced when reappraising; *y*-axis) in **a** Study 1 and **b** Study 2.

In Study 2, neither use of common markers nor use of Spanish-specific markers when reappraising in Spanish was correlated with reappraisal success (common: $r(134) = 0.12$, $p = 0.18$; Spanish-specific: $r(134) = -0.01$, $p = 0.88$). There was also no significant correlation between use of common markers when reappraising in English and reappraisal success, $r(134) = -0.07$, $p = 0.43$ (see Fig. 4b).

We suspected that these differences might be due to the different language backgrounds of the bilinguals in Studies 1 and 2. To examine this possibility, we conducted exploratory cross-study analyses comparing early and late Spanish learners.

Exploratory cross-study analyses

Table 2 shows correlations between (a) the shift in participants' use of a given distance marker when reappraising and (b) reappraisal success, for participants of different language backgrounds across both studies. For late (L2) Spanish learners, shifting the use of common markers when reappraising in either language—specifically, using fewer first-person singular pronouns and more articles—was strongly correlated with reappraisal success, similar to English monolinguals. By contrast, for early Spanish learners (L1 speakers and simultaneous bilinguals), shifting the use of common markers in Spanish was less strongly correlated with reappraisal success, and doing so in English was not correlated with reappraisal success at all. Moreover, for early Spanish learners only, increased use of "estar" when reappraising was also correlated with reappraisal success.

To explore the role of language proficiency, we divided early and late Spanish learners by their self-reported Spanish proficiency ("excellent" vs. "good"; see Supplementary Information). The correlations for these subgroups suggest that proficiency cannot fully account for the differences between early and late learners. For example, increased use of "estar" predicted reappraisal success similarly for early learners differing in proficiency, but did not predict reappraisal success for late learners. However, the correlations for some distance markers (e.g., common markers in Spanish) suggest that proficiency may play a role in certain cases (see Supplementary Table S1).

Additionally, decreased use of generic language when reappraising was weakly correlated with reappraisal success in Spanish, $r(204) = -0.16$, $p = 0.02$, but not in English, $r(297) = -0.10$, $p = 0.09$. These correlations did not reach significance for any of the subgroups in Table 2 ($ps > 0.05$).

Discussion

When English speakers regulate their emotions by reappraising potential stressors, their language becomes more psychologically distant—and the more they shift their word use in this way, the better they feel[6,7,10]. In light of cross-linguistic diversity in lexical and grammatical markers of psychological distance[14–16,20], the linguistic signatures of successful emotion regulation might also differ across languages. Heeding recent warnings about the pitfalls of overgeneralizing findings from English monolinguals[13], we expanded the study of linguistic distancing in emotion regulation to Spanish—a language proposed to offer unique tools for expressing psychological distance[16].

Across two studies, we found evidence for both cross-linguistically shared and language-specific forms of linguistic distancing in bilingual speakers of Spanish and English. When reappraising negative stimuli, participants shifted their use of distance markers common to both languages, and—at least for those in majority-Spanish speaking countries—use of Spanish-specific distance markers as well. The effects of reappraisal were driven primarily by reduced use of first-person singular pronouns and increased use of articles, "estar," and

	Spanish		English		
	Early Spanish learners	Late Spanish learners	Early Spanish learners	Late Spanish learners	English monolinguals
*Common markers**	**0.21**	**0.55**	-0.02	**0.51**	**0.22**
First-person singular pronouns*	**-0.20**	**-0.38**	-0.05	**-0.57**	**-0.23**
Articles*	**0.15**	**0.61**	-0.06	**0.47**	**0.34**
Present-tense verbs	0.01	-0.31	0.10	-0.29	-0.08
Discrepancy words	-0.10	0.02	-0.03	-0.28	-0.20
Words with > 6 letters	0.07	0.16	0.04	-0.13	**-0.21**
Spanish-specific markers	0.04	-0.02			
"Estar"	**0.20**	0.08			
Diminutives	-0.04	-0.28			
Subjunctive	-0.13	-0.13			
Positive emotion words	0.06	0.03			

Table 2. Correlation coefficients for the relation between (a) the shift in participants' use of a given distance marker (or composite of markers) when reappraising (Δ: Reappraise—Look) and (b) reappraisal success (Δ negative affect: Look—Reappraise) across Studies 1 and 2, for early Spanish learners ($n = 178$), late Spanish learners ($n = 28$), and English monolinguals (Study 1; $n = 93$). Positive and negative values indicate that increased and decreased use, respectively, was associated with reappraisal success. Bolded values indicate significant correlations ($p < 0.05$). For markers (or composites) marked with *, the correlations for early and late Spanish learners differed significantly from each other for one or both languages ($p < 0.05$; Fisher r-to-z transformation).

positive emotion words. To our knowledge, this is the first cross-linguistic evidence that people distance their language when regulating their emotions[8].

The relation between these linguistic shifts and participants' success at regulating was more complex. For U.S.-based bilinguals (Study 1), relying more on cross-linguistically common distance markers when reappraising in either language—using fewer first-person singular pronouns and more articles, for example—was associated with greater reduction in negative affect. However, these relationships were not observed for bilinguals in majority Spanish-speaking countries (Study 2), and increased use of Spanish-specific distance markers was not mirrored by reduced negative affect in either study overall. Exploratory analyses offered an intriguing reconciliation: across both studies, common markers were more strongly associated with reappraisal success for late than early Spanish learners, who only exhibited this association in Spanish. Moreover, for early learners, one Spanish-specific marker ("estar") was also associated with reappraisal success, and to a similar degree as the common markers. Additional analyses indicated that these associations were well explained by whether Spanish was participants' L1 or L2, though language proficiency may moderate associations for some distance markers.

These findings, while exploratory, suggest that the linguistic signatures of successful emotion regulation depend on language experience. Early learners of a language may achieve similar success at regulating regardless of whether they express psychological distance in cross-linguistically common or language-specific ways. By contrast, late learners may be more successful with common markers, perhaps because they find L2-specific markers less emotionally resonant[21], especially when they have relatively low L2 proficiency[24]. That said, our studies were not designed to capture fine differences between bilinguals with different language profiles, as there were far fewer late than early Spanish learners. Future research could examine such differences by testing the reverse relationship between linguistic distancing and emotion regulation in matched bilingual samples: manipulating the language used when processing aversive stimuli and assessing its emotional impact, as in previous work on distancing[6] and linguistic framing more generally[27]. If language-specific distance markers require L1-like experience or high proficiency to be signatures of successful regulation, intentionally using "estar" should reduce negative affect more for highly proficient L1 Spanish speakers than L2 or less proficient speakers. Another possibility is that English-derived markers like articles and first-person singular pronouns, though also used in Spanish when reappraising, are somewhat English-specific in how they express psychological distance. If so, these markers should reduce negative affect more in English than Spanish for L1 or highly proficient speakers of both languages.

Two other findings also warrant further investigation. First, reappraisal reduced negative affect more for U.S.-based bilinguals than bilinguals in majority Spanish-speaking countries and U.S. English monolinguals. Exploratory analyses suggested that this difference was driven by higher baseline levels of negative affect for U.S.-based bilinguals, particularly those identifying as Hispanic or Latinx. This aligns with the proposal that U.S. Hispanics exhibit resilience in the face of elevated stress reactivity due to ethnic minoritization and other forms of adversity, with surprisingly positive health outcomes[28]. Whether such resilience also derives from features of Spanish that uniquely support emotion regulation[16] remains an open question, though our findings suggest that at least one Spanish-specific feature ("estar") is a signal of emotional well-being when reappraising. More generally, future research should build on evidence that linguistic distancing reflects English speakers' mental and physical health[10,11,29,30] by investigating such relationships across languages.

Second, exploratory analyses showed that bilinguals reduced their use of generic language when reappraising and that this linguistic shift predicted reappraisal success in Spanish. These results might seem inconsistent with evidence that reappraising negative personal events *increases* the use of generic-you statements (e.g., "you take the good with the bad"), in turn promoting psychological distance[9]. This apparent contradiction may be due to a limitation of our garden-variety emotion regulation task: the highly aversive stimuli may have invited generics that reflected an immersed perspective (e.g., "spiders are gross") rather than a distanced one[12]. A task designed to elicit generics that situate negative experiences beyond the self[9,20] may provide better insight into how such language can be emotionally adaptive.

In conclusion, a cross-linguistic approach to studying linguistic distancing in emotion regulation raises important questions that an English-centric perspective might overlook[13,31]. In showing how phrases like "la vida está difícil" ("life is difficult [now]") map onto Spanish speakers' strategies for coping with personal challenges, our findings lay the foundation for identifying signatures of successful emotion regulation in other languages. This approach promises to advance our understanding of how language reflects and shapes the full spectrum of emotional experience.

Methods

Methods were approved by the Institutional Review Board at Reed College, and all relevant guidelines and regulations were followed in accordance with the Declaration of Helsinki. All participants provided informed consent.

Study 1

Participants

We recruited 100 monolingual English speakers and 125 bilingual speakers of Spanish and English on Prolific (https://www.prolific.com). All participants were located in the U.S. and had a good performance record (≥ 95% approval rating for ≥ 50 previous Prolific studies). We sought a sample size for each group similar to that of Study 1 in Nook et al.[6] ($N = 120$ pre-exclusion).

We deliberately oversampled bilinguals because our preregistered exclusion criteria included Spanish proficiency metrics for the bilingual group. Those who answered more than 1 of 3 Spanish audio comprehension questions incorrectly ($n = 4$) or rated their Spanish proficiency as lower than 7 (*good*) on an 11-point scale (0 = *none* to 10 = *perfect*; $n = 45$) were excluded. Additionally, participants from both groups were excluded if

they consistently progressed through trials without writing for a full 30 s (7 monolinguals, 1 bilingual), wrote about topics unrelated to the images (1 monolingual, 3 bilinguals), consistently wrote in English in the Spanish block, or vice versa (3 bilinguals), or reported that they did not reside in the U.S. (1 bilingual). An additional 16 participants (5 monolinguals, 11 bilinguals) failed an initial attention check ("check the option 'Other' below and enter the number 8 in the text box of this option") and were prevented from completing the study.

Our final sample consisted of 93 monolinguals (66% female, 31% male, 3% nonbinary or gender-fluid; 84% White, 1% Hispanic/Latinx; age: $M=39$ years, $SD=14$, range = 20–74) and 70 bilinguals (47% female, 50% male, 3% nonbinary or gender-fluid; 39% White, 67% Hispanic/Latinx; age: $M=33$, $SD=12$, range = 19–72; Spanish proficiency: $M=8.17$, $SD=1.09$; English proficiency: $M=9.69$, $SD=0.63$). Within the bilingual group, 56% reported learning both Spanish and English from early in childhood (before age 5), 37% reported learning English first, and 7% reported learning Spanish first.

A power analysis using G*Power 3.1[32] indicated that our group sizes were sufficient for detecting the large within-subjects effects of reappraisal on self-reported negative affect ($d=-0.95$) and linguistic distancing ($d=0.72$) observed in Study 1 of Nook et al.[6] at $p<0.05$ and power of 0.99 (difference between Reappraise Negative and Look Negative conditions), for which just 38 participants were required. Based on the duration of pilot experiments, monolingual and bilingual participants received $2.50 and $5.34, respectively, upon completing the study.

Materials

We used the same two lists of 20 negative images of people and objects (e.g., a crying baby, a bloody knife) as Nook et al.[6]. The images were obtained from the Open Affective Standardized Image Set (OASIS)[33]. Each list (A and B) was divided into two sublists matched for valence and arousal, based on normed ratings on a 1–9 scale where lower scores are more negative or less arousing. The sublists did not differ significantly in valence (List A1: $M=2.36$, $SD=0.43$; List A2: $M=2.37$, $SD=0.44$; item analysis: $t(18)=0.01$, $p=0.99$; List B1: $M=2.38$, $SD=0.43$; List B2: $M=2.38$, $SD=0.59$; $t(18)=0.01$, $p=0.99$), nor in arousal (List A1: $M=4.25$, $SD=0.69$; List A2: $M=4.23$, $SD=0.44$; $t(18)=0.07$, $p=0.95$; List B1: $M=4.26$, $SD=0.43$; List B2: $M=4.24$, $SD=0.59$; $t(18)=0.10$, $p=0.92$).

Design and procedure

Each participant completed a standard emotion regulation task[6], either responding naturally to images (Look trials) or rethinking their meaning to make them less negative (Reappraise trials). Monolinguals were randomly assigned to receive one of the two image lists. The 20 images were presented in a single block, with the 10 images from one sublist presented on Look trials and those from the other sublist presented on Reappraise trials. Bilinguals completed two such blocks, one in English and one in Spanish; each block was paired with one of the two lists, resulting in 40 total trials. Within each block, Look and Reappraise trials were randomly intermixed. The assignment of sublists to conditions (Look and Reappraise) was counterbalanced across participants. For bilinguals, the assignment of lists to the English and Spanish blocks and the order of the two blocks were also counterbalanced across participants.

The study was administered online via Qualtrics. After passing an attention check and providing informed consent in English, participants completed the emotion regulation task. For bilinguals, the instructions for each block were presented in the language assigned to that block. Following Nook et al.[6], participants were instructed that the cue word "LOOK" (Spanish: "MIRE") meant that they should "just look at the picture and let yourself feel whatever that image makes you feel," while the cue word "CHANGE" ("CAMBIE") meant that they should "try to think about the image in a new way that makes you feel better about it" (e.g., "imagine that the image is fake" or "part of a positive story"). Instructions were translated into Spanish and back-translated by native Spanish speakers. Full instructions in each language are available on our Open Science Framework (OSF) page.

On each trial, one of the two cue words was shown above an image. Participants transcribed their thoughts and feelings about the image into a text box below it. The page advanced automatically after 30 s. On the next screen, participants rated their negative affect ("How bad do you feel?"/"Qué tan mal se siente usted?") on a 7-point scale (1 = *Not bad at all*/*Nada mal* to 7 = *Extremely bad*/*Malísimo*).

After the emotion regulation task, all participants answered a series of demographic questions in English. Bilinguals then completed a brief Spanish proficiency task, adapted from a standardized assessment (Common European Framework of Reference for Languages, C1 level: "proficient user"[34]). They listened to a 38-s clip of a Spanish dialogue and answered 3 multiple-choice comprehension questions in Spanish. Finally, all participants were debriefed in English.

Study 2

Participants

We recruited 150 Spanish–English bilinguals from majority Spanish-speaking countries on Prolific. All participants had ≥ 95% approval on ≥ 50 previous Prolific studies. Analogous to Study 1, we excluded participants who rated their English proficiency as lower than 7 (*good*) on an 11-point scale (mean of 3 ratings: speaking, understanding, reading; $n=8$), consistently progressed through trials without writing for a full 30 s ($n=4$), or consistently wrote in English in the Spanish block, or vice versa ($n=2$). We also excluded one participant who reported residing in the U.S. ($n=1$). Two additional participants failed the initial attention check and were prevented from completing the study.

Our final sample consisted of 136 participants, nearly twice the size of the bilingual group in Study 1 (60% male, 34% female, 6% nonbinary or gender-fluid; age: $M=29$ years, $SD=8$, range = 18–57; Spanish proficiency: $M=9.81$, $SD=0.45$; English proficiency: $M=8.78$, $SD=0.85$). All participants were located in Mexico ($n=69$), Chile ($n=34$), or Spain ($n=33$). The majority of participants (75%) reported learning Spanish first and English

at age 5 or later; 24% reported learning both languages before age 5, and 1% reported learning English first. Each participant received $5 upon completing the study.

Materials, design, and procedure
Participants completed the same emotion regulation task as the bilingual group in Study 1. As all participants were from majority Spanish-speaking countries, we omitted the auditory Spanish proficiency task. All other aspects of the procedure were identical to Study 1.

Processing and coding of text responses

Prior to analysis, participants' text responses in both studies were proofread for spelling by a native speaker of the language in which the response was written, following Nook et al.[6].

Composite measures of linguistic distancing
To compute the composite measure comprising markers of psychological distance common to English and Spanish[6,17], we used the 2007 English dictionary in LIWC-22[26,35] and its Spanish counterpart[36]. We obtained the proportion of words in each text response from each of the following categories: first-person singular pronouns, present-tense verbs, articles, discrepancy words, and words with more than 6 letters. We *z*-scored the proportion of words from each category separately for each group of participants (Study 1) and for each language (for bilinguals in both studies). Then we reverse-scored the *z*-scored proportions of first-person singular pronouns, present-tense verbs, and discrepancy words, and averaged the resulting values from all 5 categories.

To compute the Spanish-specific composite distancing measure, we used LIWC-22 to obtain the proportion of words in each Spanish text response that came from the four categories identified by Llabre[16]: *estar*, diminutives, the subjunctive mood, and positive emotion words. For *estar* (and its conjugations) and diminutives, we created a custom LIWC dictionary (available on our OSF page). For the subjunctive mood and positive emotion words, we used the 2007 Spanish dictionary in LIWC-22. The composite measure was computed by *z*-scoring the proportion of words from each category and averaging the 4 resulting values.

Other linguistic measures
For each text response, we manually coded two additional linguistic features of interest that could not be obtained from LIWC: (1) generic statements (e.g., "los bebés lloran"/"babies cry"), and (2) first-person singular language in Spanish, including verbs with no pronoun (e.g., "quiero ayudar," *I want to help*).

A given response was coded as generic if it contained one or more statements attributing a property to a category in general or to an abstract or idealized concept (e.g., "we" (humans), "losing someone," "Mother Nature")[20,37,38]. Following previous research[37], a response was considered generic even if the generic statement was framed (e.g., "*it is nice that* we live in a world where we can dispose of our belongings") or hedged (e.g., "tornadoes *can be* frightening"), but not if it contained a qualifier (e.g., "*sometimes* the environment resurges") or a quantifier (e.g., "*some* animals live and *some* don't"; emphases added).

A given Spanish response was coded as first-person singular if it contained one or more first-person singular pronouns or conjugated verbs. As pronouns are routinely dropped in Spanish[20], measuring first-person singular pronouns alone (as in the English-derived composite measure of linguistic distancing) does not fully capture self-reference in Spanish. For example, the phrase "quiero ayudar" (*I want to help*) would be coded as first-person but not counted by LIWC-22 as an instance of first-person singular pronouns because it omits the pronoun "yo" (*I*).

For both Spanish and English responses, two native speakers blind to condition independently coded 20% of the responses in each study. For generic language, interrater reliability (κ) was 0.67 for the English responses and 0.80 for the Spanish responses across studies, indicating substantial agreement[39]. For first-person singular language in Spanish, reliability was 0.96 across studies, indicating near-perfect agreement. To ensure consistency within and across languages, discrepancies in each language were resolved through a three-way discussion among the two coders and one of the coders for the other language. For each language, one coder proceeded to code the remaining 80% of the responses (for coding results, see our OSF page).

In both studies, the results showed the same pattern regardless of whether self-reference was measured by first-person singular pronouns (obtained from LIWC-22 and part of the preregistered composite of cross-linguistically common distance markers) or first-person singular language more generally (manually-coded and exploratory). Therefore, we report our analyses for the former measure in the Results section.

Data availability

We preregistered our methods and analysis plans on AsPredicted.org. Our preregistrations, materials, and data are available on the Open Science Framework (OSF; https://osf.io/gujwv/).

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References

1. Gross, J. J. Emotion regulation: Current status and future prospects. *Psychol. Inq.***26**, 1–26 (2015).
2. Davis, J. I., Gross, J. J. & Ochsner, K. N. Psychological distance and emotional experience: What you see is what you get. *Emotion***11**, 438–444 (2011).
3. Denny, B. T. & Ochsner, K. N. Behavioral effects of longitudinal training in cognitive reappraisal. *Emotion***14**, 425–433 (2014).
4. Kross, E., Davidson, M., Weber, J. & Ochsner, K. Coping with emotions past: the neural bases of regulating affect associated with negative autobiographical memories. *Biol. Psychiatry***65**, 361–366 (2009).

5. Ray, R. D., McRae, K., Ochsner, K. N. & Gross, J. J. Cognitive reappraisal of negative affect: Converging evidence from EMG and self-report. *Emotion***10**, 587–592 (2010).
6. Nook, E. C., Schleider, J. L. & Somerville, L. H. A linguistic signature of psychological distancing in emotion regulation. *J. Exp. Psychol. Gen.***146**, 337–346 (2017).
7. Nook, E. C., Vidal Bustamante, C. M., Cho, H. Y. & Somerville, L. H. Use of linguistic distancing and cognitive reappraisal strategies during emotion regulation in children, adolescents, and young adults. *Emotion***20**, 525–540 (2020).
8. Nook, E. C. The promise of affective language for identifying and intervening on psychopathology. *Affect. Sci.***4**, 517–523 (2023).
9. Orvell, A., Kross, E. & Gelman, S. A. How, "you" makes meaning. *Science***355**, 1299–1302 (2017).
10. Shahane, A. D. & Denny, B. T. Predicting emotional health indicators from linguistic evidence of psychological distancing. *Stress Health***35**, 200–210 (2019).
11. Nook, E. C., Hull, T. D., Nock, M. K. & Somerville, L. H. Linguistic measures of psychological distance track symptom levels and treatment outcomes in a large set of psychotherapy transcripts. *Proc. Natl. Acad. Sci. USA***119**(7119), e2114737119. https://doi.org/10.1073/pnas.2114737119 (2022).
12. Kross, E. *et al.* Self-talk as a regulatory mechanism: How you do it matters. *J. Pers. Soc. Psychol.***106**, 304–324 (2014).
13. Blasi, D. E., Henrich, J., Adamou, E., Kemmerer, D. & Majid, A. Over-reliance on English hinders cognitive science. *Trends Cogn. Sci.***26**, 1153–1170 (2022).
14. Dryer, M. S. Definite articles in *The world atlas of language structures online* (v2020.3) (eds. Dryer, M. S. & Haspelmath, M.). http://wals.info/chapter/37 (2013).
15. Lupyan, G. & Dale, R. Language structure is partly determined by social structure. *PLoS One***5**, e8559. https://doi.org/10.1371/journal.pone.0008559 (2010).
16. Llabre, M. M. Insight into the Hispanic paradox: the language hypothesis. *Perspect. Psychol. Sci.***16**, 1324–1336 (2021).
17. Pérez-Leroux, A. Subjunctive mood in Spanish child relatives: at the interface of linguistic and cognitive development in *Children's language, vol. 11: interactional contributions to language development* (eds. Nelson, K. E., Aksu-Koç, A. & Johnson, C. E.), 69–93 (Lawrence Erlbaum Associates, 2001).
18. Dodds, P. S. *et al.* Human language reveals a universal positivity bias. *Proc. Natl. Acad. Sci. USA***112**, 2389–2394 (2015).
19. Mehl, M. R., Robbins, M. L. & Holleran, S. E. How taking a word for a word can be problematic: Context-dependent linguistic markers of extraversion and neuroticism. *J. Methods Meas. Soc. Sci.***3**, 30–50 (2012).
20. Salvador, C. E., Orvell, A., Kross, E. & Gelman, S. A. How Spanish speakers express norms using generic person markers. *Sci. Rep.***12**, 5076. https://doi.org/10.1038/s41598-022-08675-2 (2022).
21. Pavlenko, A. Emotion and emotion-laden words in the bilingual lexicon. *Biling. Lang. Cogn.***11**, 147–164 (2008).
22. Harris, C. L., Ayçiçeği, A. & Gleason, J. B. Taboo words and reprimands elicit greater autonomic reactivity in a first language than in a second language. *Appl. Psycholinguist.***24**, 561–579 (2003).
23. Harris, C. L. Bilingual speakers in the lab: Psychophysiological measures of emotional reactivity. *J. Multiling. Multicult. Dev.***25**, 223–247 (2004).
24. Champoux-Larsson, M.-F. & Nook, E. C. How first- and second-language emotion words influence emotion perception in Swedish-English bilinguals. *Biling. Lang. Cogn.*https://doi.org/10.1017/S1366728923000998 (2024).
25. Degner, J., Doycheva, C. & Wentura, D. It matters how much you talk: on the automaticity of affective connotations of first and second language words. *Biling. Lang. Cogn.***15**, 181–189 (2012).
26. Boyd, R. L., Ashokkumar, A., Seraj, S. & Pennebaker, J. W. *The development and psychometric properties of LIWC-22*. https://www.liwc.app (2022).
27. Flusberg, S. J., Holmes, K. J., Thibodeau, P. H., Nabi, R. & Matlock, T. The psychology of framing: how everyday language shapes the way we think, feel, and act. *Psychol. Sci.Public Interest* (in press).
28. Gallo, L. C., Penedo, F. J., de Espinosamonteros, K. & Arguelles, W. Resiliency in the face of disadvantage: Do Hispanic cultural characteristics protect health outcomes?. *J. Pers.***77**, 1707–1746 (2009).
29. Cohen, K. A., Shroff, A., Nook, E. C. & Schleider, J. L. Linguistic distancing predicts response to a digital single-session intervention for adolescent depression. *Beh. Res. Ther.***159**, 104220. https://doi.org/10.1016/j.brat.2022.104220 (2022).
30. Shahane, A. D., Fagundes, C. P., Buka, S. L. & Denny, B. T. Associations between linguistic markers of emotion regulation and cardiovascular disease-related inflammation. *Psychoneuroimmunol. J.***12**, 246121. https://doi.org/10.32371/pnij/246121 (2021).
31. Wolff, P. & Holmes, K. J. Linguistic relativity. *WIREs Cogn. Sci.***2**, 253–265 (2011).
32. Faul, F., Erdfelder, E., Lang, A.-G. & Buchner, A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Beh. Res. Methods***39**, 175–191 (2007).
33. Kurdi, B., Lozano, S. & Banaji, M. R. Introducing the open affective standardized image set (OASIS). *Beh. Res. Methods***49**, 457–470 (2017).
34. Council of Europe. *Common European framework of reference for languages: learning, teaching, assessment* (Cambridge University Press, 2001).
35. Pennebaker, J. W., Chung, C. K., Ireland, M., Gonzales, A. & Booth, R. J. *The development and psychometric properties of LIWC2007* (LIWC, 2007).
36. Ramírez-Esparza, N., Pennebaker, J. W., García, F. A. & Suriá, R. L. psicología del uso de las palabras: Un programa de computadora que analiza textos en español. *Rev. Mex. Psicol.***24**, 85–99 (2007).
37. DeJesus, J. M., Callanan, M. A., Solis, G. & Gelman, S. A. Generic language in scientific communication. *Proc. Natl. Acad. Sci. USA***116**, 18370–18377 (2019).
38. Vasilyeva, N. & Lombrozo, T. Structural thinking about social categories: evidence from formal explanations, generics, and generalization. *Cognition***204**, 104383. https://doi.org/10.1016/j.cognition.2020.104383 (2020).
39. Landis, J. R. & Koch, G. G. The measurement of observer agreement for categorical data. *Biometrics***33**, 159–174 (1977).

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Author contributions

K.J.H., L.K., and E.C.G. conceived the study. E.C.G. translated materials and developed analysis tools. K.J.H. and L.K. prepared materials and collected data. K.J.H., L.K., and E.C.G. analyzed and interpreted data. All authors proofread and coded text responses. K.J.H. drafted the manuscript, and L.K., D.B.A., and E.C.G. provided critical revisions. All authors approved the final version of the manuscript for submission.

Competing interests

The authors declare no competing interests.

Additional information

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