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On language and thought: Bilingual experience influences semantic associations

Siqi Ning [*], Sayuri Hayakawa, James Bartolotti, Viorica Marian

Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL, 60208, USA

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ABSTRACT

Language can influence cognition in domains as varied as temporal processing, spatial categorization, and color perception (Casasanto & Boroditsky, 2008; Levinson & Wilkins, 2006; Winawer et al., 2007). Here, we provide converging behavioral and neural evidence that bilingual experience can change semantic associations. In Experiment 1, Spanish- and English-speaking bilinguals rated semantically unrelated picture pairs (e.g., *cloud-present*) as significantly more related in meaning than English monolinguals. Experiment 2 demonstrated that bilinguals who were highly proficient in Spanish and English rated both semantically related (e.g., *door-window*) and unrelated picture pairs (e.g., *dress-snail*) as more related than monolinguals and low-proficiency bilinguals. Experiment 3 added ERP measures to provide a more sensitive test of the bilingual effect on semantic ratings, which was assessed through the use of linguistic stimuli (related and unrelated words instead of pictures) and a different bilingual population (Korean-English bilinguals). Bilingualism was associated with a significantly smaller N400 effect (i.e., N400 for unrelated - related), suggesting that bilinguals processed related and unrelated pairs more similarly than monolinguals; this result was coupled with a non-significant behavioral trend of bilinguals judging unrelated words as more related than monolinguals did. Across the three experiments, results show that bilingual experience can influence perceived semantic associations. We propose that bilinguals' denser and more interconnected phonological, orthographic and lexical systems may change the links between semantic concepts. Such an account is consistent with connectionist models of language that allow for phonological and lexical influences on conceptual representations, with implications for models of bilingual language processing.

1. Introduction

If you ask a Mandarin-English bilingual what animal he or she counts to fall asleep, there is a good chance that you might hear "*goats*" instead of "*sheep.*" In Mandarin, goats and sheep can both be referred to with the term "*yang*" (羊) – goat is "*shan yang*" ("*shan*" meaning mountain), and sheep is "*mian yang*" ("*mian*" meaning cotton). Because of similarities in both phonology and semantics, Mandarin speakers think of goats and sheep as highly similar. To Mandarin speakers who also know English, not only are goats and sheep highly similar, but sheep and sleep are also highly related (driven by both their phonological similarity in English and the cultural practice of counting sheep). Because "*sheep*" is associated with both "*sleep*" and "*goat,*" Mandarin-English bilinguals form

* Corresponding author.
E-mail address: siqining2022@u.northwestern.edu (S. Ning).

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associations between *sleep* and *goat* (See Fig. 1), resulting in the practice of counting goats to fall asleep. While these new associations may be indirect early on, with enough repeated co-activations, stronger direct links may begin to develop. We propose that, over time, the accumulation of associations like "*sleep-sheep-goat*" yields a more flexible and interconnected semantic network, to the extent that bilinguals may rate any two concepts as more related to each other than monolinguals.

Whether language can affect thought is a frequent topic of discussion. Although the strong Whorfian hypothesis that language determines thought is controversial (Heider, 1972; Lakoff, 1987), recent research has shown that language influences mental representation of space (Levinson & Wilkins, 2006), time (Casasanto & Boroditsky, 2008), motion (Slobin, 2003), and color (Winawer et al., 2007). Furthermore, there is evidence that the acquisition of a second language can shift individuals' category boundaries of colors, containers, and movements, etc. (Ameel, Malt, Storms, & Van Assche, 2009; Ameel, Storms, Malt, & Sloman, 2005; Malt, Li, Pavlenko, Zhu, & Ameel, 2015; Malt & Majid, 2013; Malt, Sloman, Gennari, Shi, & Wang, 1999). For instance, an English speaker may label three different objects as a "bottle," a "jar," and a "container," whereas a Chinese speaker may label the same three objects using a single word (Malt et al., 1999). Intriguingly, bilinguals often adopt naming conventions that integrate patterns from both known languages when labeling in *either* language (Ameel et al., 2005, 2009). Here, we explore whether the effects of bilingual experience extend beyond conventions in linguistic categorization to impact the perceived relationship between the concepts themselves.

At the neural level, the ways in which concepts become associated can be explained by Hebbian learning (Brunel, 1996; Hebb, 1949; Mongillo, Amit, & Brunel, 2003), which can be summarized as "neurons that fire together wire together." In other words, neurons that are repeatedly coactivated will develop stronger connections between each other, with the strength of their association directly proportional to how frequently they respond together. In cognitive models, these neuronal connections are directly related to the activation of nodes in a semantic network (Anderson, 1983). Conceptual knowledge is often hypothesized to be organized as a network of mutually interconnected nodes, the activation of which represents the retrieval of that information.

In many connectionist models, this conceptual/semantic network is depicted as one of at least three levels of language representation. In addition to the conceptual/semantic level, the lexical level contains our mental representations of words and their grammatical features, and a third level contains phonological information (e.g., Caramazza, 1997; Dell, 1986; Levelt, Roelofs, & Meyer, 1999; McClelland & Rumelhart, 1981). In the process of language production, activation of a node would spread to nearby related nodes. For example, activation of the conceptual node "*cat*" would spread to related nodes like "*dog*," "*mouse*," and "*tail*," which are semantically related to "*cat*," while at the phonological level, /kæt/ would activate /ræt/,/mæt/, /hæt/, etc. which all share phonological features. Just as neurons that fire together wire together, co-activations of nodes serve to strengthen their connections.

Notably, according to models such as Dell's *Interactive Activation Model* (Dell, 1986) and the *Bilingual Language Interaction Network for Comprehension of Speech* (*BLINCS*; Shook & Marian, 2013), activation can spread not only within, but also across levels (see Fig. 2). Semantic associations between concepts may therefore be affected not only by inherent semantic relationships like "*cat-dog*," but also by phonological (e.g., "*cat-mat*"), morphological (e.g., "*physics-physician*"), and syntactic associations (e.g., grammatical gender like "*el/la*"). Because patterns of phonological and lexical associations are different across languages, an English speaker may perceive a cat and a mat to be more semantically related due to their phonological similarities, while a Spanish speaker may instead perceive an

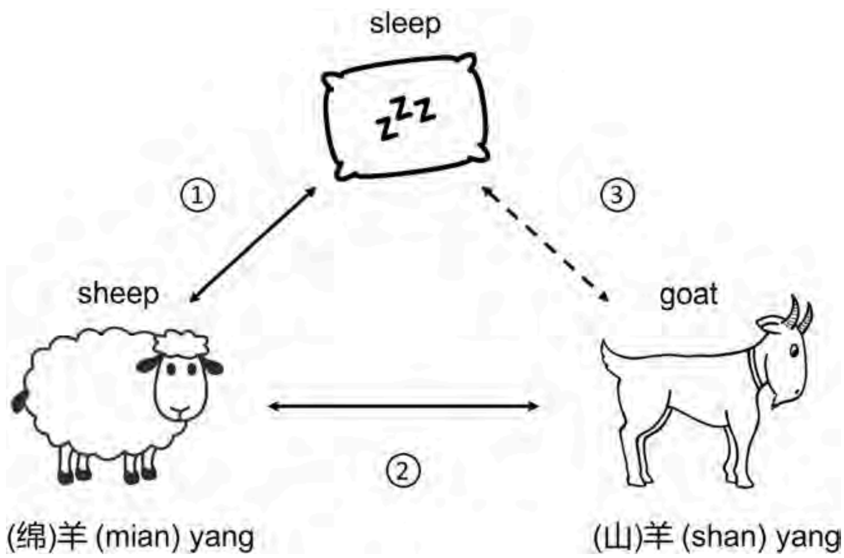

Fig. 1. If cross-linguistic differences in the features of two languages can influence bilinguals' semantic organizations, Mandarin-English bilinguals may have:

1) increased semantic associations for phonologically related English words like "*sleep*" and "*sheep*".
2) increased semantic associations for phonologically related Mandarin words like "*mian yang*" (sheep) and "*shan yang*" (goat),
3) increased semantic associations between "*sleep*" and "*goat*" through indirect cross-linguistic phonological mediations, with direct links likely developing over time.

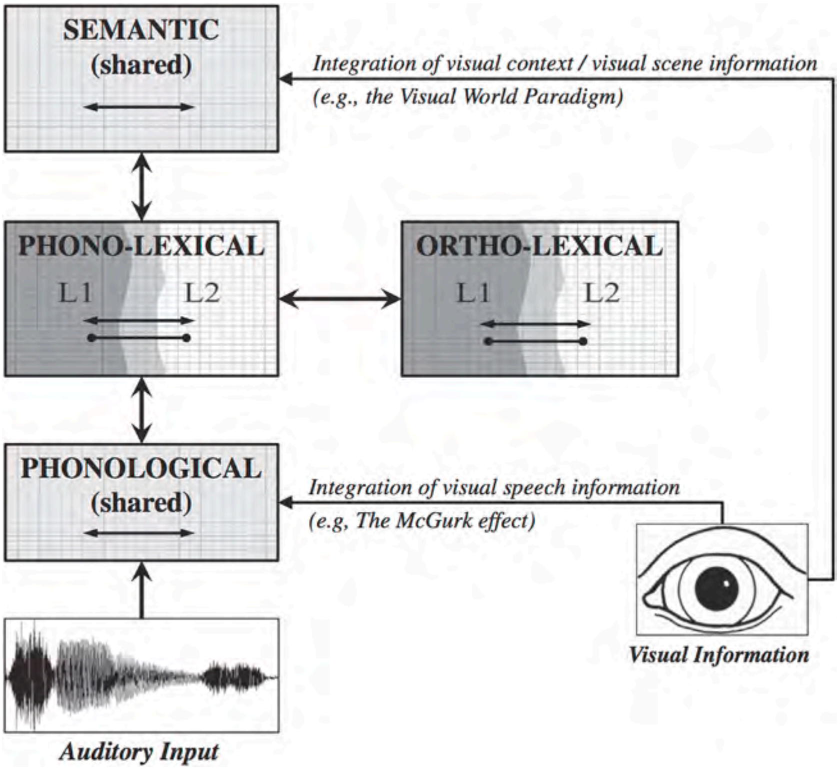

Fig. 2. The Bilingual Language Interaction Network for Comprehension of Speech (BLINCS) model (From Shook & Marian, 2013, Fig. 1.).

increased association between a cat (*gato*) and a duck *(pato*). While the debate continues on the exact organization of bilinguals' two languages at different levels of representation, evidence from studies such as those using cross-language semantic priming provide compelling evidence that the conceptual level is largely shared by both languages (e.g., Kirsner, Smith, Lockhart, King, & Jain, 1984). Furthermore, studies suggest that bilinguals may have non-selective access to lexical representations of different languages, meaning that words in both languages can become simultaneously activated (Brysbaert, Van Dyck, & Van De Poel, 1999; Colomé, 2001). For instance, non-selective lexical access is evidenced by facilitation from cross-linguistic cognates, as well as interference from phonologically-overlapping competitors across languages (Dijkstra, Grainger, & Van Heuven, 1999; Kroll & Stewart, 1994; Marian & Spivey, 2003). Indeed, many of the leading models in the field, such as the *Revised Hierarchical Model* (*RHM*; Kroll & Stewart, 1994), *Bilingual Interactive Activation Model* (*BIA/BIA*+, Dijkstra & van Heuven, 2002; Van Heuven, Dijkstra, & Grainger, 1998), and *BLINCS* (Shook & Marian, 2013) propose highly interactive or partially integrated lexical stores for bilinguals' two languages. If bilinguals have non-selective access to the lexical and phonological space of their two languages with feedback mechanisms across levels of representations, we reasoned that bilinguals may have more linguistically mediated associations compared to monolinguals (e.g., both "*cat-mat*" in English and "*gato (cat)-pato (duck)*" in Spanish).

Moreover, due to the density of connections in the network, it is likely that even distant nodes that are not directly associated in any language would have shorter paths linking them because of additional intervening nodes. For instance, the Spanish-English bilingual in our example may perceive increased associations between *mats* and *ducks* because of the mediating node "*cat*" ("*mat*"-"*cat/gato*"-"*pato/duck*"). Semantically mediated priming effects (e.g., *"lion-tiger-stripes"*) have already been found in monolingual naming and lexical decision tasks (McKoon & Ratcliff, 1992; McNamara & Altarriba, 1988), and cross-linguistic false cognates and homophones have been shown to influence bilinguals' semantic associations (Degani, Prior, & Hajajra, 2017; Degani, Prior, & Tokowicz, 2011; Lev-Ari & Keysar, 2014). For example, Degani et al. (2017) found that Arabic-Hebrew bilinguals were more likely to judge two unrelated Hebrew words as semantically related if the two words were connected by a hidden false-cognate in Arabic (e.g., *horse-egg*, with /sus/ meaning "horse" in Hebrew but "chick" in Arabic). Similarly, Degani et al. (2011) found that English-Hebrew bilinguals perceived unrelated English words as more semantically related when they shared a Hebrew translation (e.g., *tool-dish*, which both translate to "kli" in Hebrew), demonstrating that overlapping word forms can influence the perceived similarity of concepts even when they are semantically unrelated in either language. In sum, there is compelling evidence that semantic similarity can be influenced by linguistic features, and that the parallel activation of multiple languages can lead bilinguals to perceive relationships that monolinguals do not (i.e., akin to the "*sleep-sheep-goat*" example discussed earlier). The present study extends the inquiry one step further by asking whether the accumulation of cross-linguistic associations would have a cascading effect on the semantic network – that is, whether relationships are forged even between concepts that share increasingly distant lexical and semantic links (e.g., **pill**-pillow-sleep-sheep-**goat …)**, with the end result being that all concepts are more related to each other in a bilingual's mind.

We hypothesize that bilinguals' greater number of connections at the phonological and lexical levels may cause their conceptual nodes to be closer linked than those of monolinguals. Based on this argument, we should observe that bilinguals' judgments of semantic relatedness will differ from those of monolinguals. This hypothesis was evaluated in two behavioral experiments and one ERP experiment. In each experiment, monolinguals and bilinguals were asked to rate how related in meaning two concepts were on a Likert scale. Across experiments, we manipulated characteristics related to the bilingual individual (i.e., proficiency), the task (i.e., mode of presentation), and the concepts themselves (i.e., semantic similarity) to examine the effect of bilingualism on semantic associations.

2. Experiment 1: bilinguals vs. monolinguals

Experiment 1 aimed to test whether bilinguals perceive a closer relationship between concepts compared to monolinguals.

2.1. Methods

2.1.1. Participants

Twenty-seven English monolinguals (mean age = 22.91 years; 9 males) and 19 Spanish- and English-speaking bilinguals (mean age = 22.7 years; 6 males) participated for monetary compensation. In this and all following experiments, informed consent was obtained in accordance with Northwestern University's Institutional Review Board (IRB). After the experiment, participants completed the *Language Experience and Proficiency Questionnaire* (Marian, Blumenfeld, & Kaushanskaya, 2007) and a battery of cognitive tasks. Bilingual and monolingual participants did not differ in English proficiency, nonverbal IQ (matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI); PsychCorp, 1999) or working memory (digit span and non-word repetition subtests of the Comprehensive Test of Phonological Processing; Wagner, Torgesen, Rashotte, & Pearson, 1999), *ps* > .05. The monolingual group did, however, report acquiring English earlier than bilinguals ($t(18.89) = 4.14$, $p < .001$; see Table 1). Among the bilinguals, 10 reported acquiring Spanish first, 2 acquired English first, and 7 were simultaneous bilinguals. Regarding language dominance, 13 reported being English-dominant, 3 were Spanish-dominant, and 3 had equal proficiency across their two languages.

2.1.2. Stimuli

Thirty black and white line drawings were chosen from the International Picture Naming Project (IPNP) database (Bates et al., 2000) or independently normed on Amazon's Mechanical Turk using black and white drawings found through Google Images. From these, we constructed fifteen picture pairs that were phonologically unrelated in either English or Spanish (e.g., "*cloud-present*", which is "*nube-regalo*" in Spanish). Labels of pictures were matched on log word frequency (Brysbaert & New, 2009), age of acquisition (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012), and concreteness, familiarity, and imageability (Coltheart, 1981).

2.1.3. Procedure

Participants were given a printed test booklet containing picture pairs. They were asked to judge how related in meaning each pair of pictures were by circling a number on the 1-9 Likert scale underneath the pictures, with 1 meaning "not at all related" and 9 meaning "completely related".

2.2. Results and discussion

Semantic ratings were analyzed using multinomial logistic mixed effects regression, with a fixed effect of group (contrasts effect-coded and weighted by sample size: monolingual = −0.41 vs. bilingual = +0.59), random intercepts for participant and item, as well as a by-item random slope for group (i.e., the "maximal" random effects structure, (Barr, Levy, Scheepers, & Tily, 2013). Model comparison confirmed that the model including the fixed effect was a better fit than the null model ($\chi^2(1) = 4.75$, $p = .029$). There was a significant effect of group (*Estimate* = 0.66, *SE* = 0.29, $z = 2.22$, $p = .026$), with higher ratings for bilinguals ($M = 3.02$, $SE = 0.17$) than monolinguals ($M = 2.54$, $SE = 0.69$). See Fig. 3.

In this experiment, bilinguals were found to rate picture pairs as more similar in meaning than monolinguals, supporting our hypothesis that concepts are more closely associated in a bilingual's mind. By using picture stimuli, the results also indicate that overt language cues are not necessary to observe the conceptual level differences between bilinguals and monolinguals. With a basic bilingual effect on semantic associations discovered, in the next few experiments, we explored the strength of this effect under different circumstances.

3. Experiment 2: inherent relatedness and bilingual proficiency

Having established the basic effect in Experiment 1, Experiment 2 explored whether the bilingual increase in semantic relatedness was moderated by stimulus- and participant-related variables. One objective of Experiment 2 was to examine whether the bilingual-monolingual difference in semantic associations is modulated by the inherent semantic relatedness of the concepts themselves. On the one hand, it is possible that when two concepts are already strongly associated, a denser network would do little to increase their perceived relationship. In that case, a bilingual effect might only be seen for unrelated concepts. On the other hand, the effect of having additional connections may be additive and strengthen all associations regardless of inherent relatedness. Experiment 2 therefore aimed to replicate the bilingualism effect found in Experiment 1, and to examine whether the effect holds for both inherently semantically related and unrelated concept pairs.

Table 1
Experiment 1 participant language backgrounds, means and SDs.

Measure	Monolinguals	Bilinguals
English AoA	0.33 (0.62)	3.53 (3.32)
Spanish AoA	–	1.44 (1.65)
English Proficiency	9.70 (0.53)	9.54 (0.72)
Spanish Proficiency	–	8.81 (0.88)

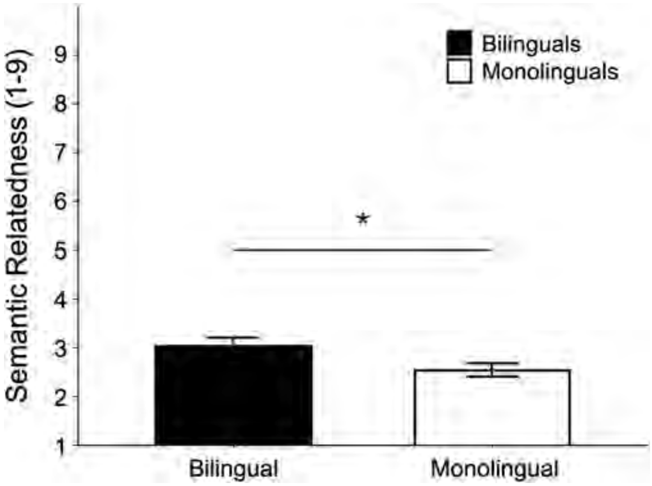

Fig. 3. Mean semantic relatedness ratings of picture pairs on the 1-9 scale (1: "not at all related"; 9: "completely related") by bilinguals and monolinguals in Experiment 1. Error bars represent standard error.

A second objective of Experiment 2 was to examine whether bilinguals' semantic associations are influenced by proficiency in their non-dominant language. Language proficiency has been found to influence many aspects of bilingual lexical processing (Van Hell & Tanner, 2012). According to the *Revised Hierarchical Model* of bilingual language processing (Kroll & Stewart, 1994), proficiency modulates lexical-semantic relationships. Connections between L2 lexical items and their conceptual representations are proposed to be initially mediated through the first language, but then gradually strengthen as L2 proficiency improves. We predicted that the effect of bilingualism on semantic associations should be more pronounced in high-proficiency bilinguals, for whom both languages are likely to have forged direct connections with conceptual referents.

3.1. Methods

3.1.1. Participants

Eighteen English monolinguals (ML; mean age = 23.77; 5 males) and 18 Spanish- and English-speaking bilinguals (mean age = 24.53; 2 males) were included. Participants completed the LEAP-Q, the NIH toolbox Cognitive Battery, and the WASI. Bilingual participants also performed the LexTALE-Español Spanish lexical decision task (Izura, Cuetos, & Brysbaert, 2014). Based on their combined age of acquisition, self-rated Spanish proficiency scores, and LexTALE performance, bilingual participants were divided into high-proficiency bilinguals (HBL; N = 11) and low-proficiency bilinguals (LBL; N = 7). Participants' order of English and Spanish acquisition varied. Out of the 11 HBLs, 4 acquired Spanish as their first language, 4 acquired English as their first language, and 3 acquired both simultaneously. Out of the 7 LBLs, all acquired English as their first language. All participants reported English as their dominant language. Across groups, participants were matched on age, performance IQ, and scores on the card sort task and pattern comparison task, as well as English age of acquisition and English proficiency. LBLs acquired Spanish significantly later than HBLs, and

Table 2
Experiment 2 participants' language backgrounds, means and SDs.

Measure	ML	HBL	LBL	
English AoA	0.72 (0.96)	1.56 (2.13)	0.33 (0.82)	
Spanish AoA	–	5.11 (7.74)	12.00 (3.48)	*
English Proficiency	9.80 (0.40)	9.30 (1.06)	9.66 (0.66)	
Spanish Proficiency	–	8.09 (1.31)	5.90 (1.15)	**
LexTALE-Esp	–	0.70 (0.14)	0.56 (0.08)	*

Note: ** = $p < .01$; * = p < .05.

had significantly lower Spanish proficiency, as assessed by both self-report and the LexTALE-Esp (see Table 2). Participants in this experiment did not participate in any other experiments listed in this study.

3.1.2. Stimuli

A total of 240 black and white line drawings were selected from the IPNP and Google Images to form 120 picture pairs. Of these picture pairs, 20 were highly related (e.g., "*door-window*"), and 100 were unrelated (e.g., "*dress-snail*"). Images obtained from the IPNP were selected based on high naming consistency. Pictures obtained from Google Images were independently normed by 20 English monolinguals and 20 Spanish-English bilinguals recruited online. Naming reliability in English was 84.4% (SD = 8.7), and in Spanish was 85.2% (SD = 14.3). Picture pairs were matched on concreteness, familiarity, imageability, and meaningfulness.

3.1.3. Procedure

In each trial, participants saw two pictures side by side on a computer screen. They were asked to enter a number from 1 to 9 to rate how related in meaning the two pictures were to each other, with 1 meaning "completely unrelated" and 9 meaning "completely related". Participants then pressed "Enter" to move on to the next pair of pictures.

3.2. Results and discussion

Semantic ratings were analyzed using multinomial logistic mixed effects regression, with fixed effects of group (contrast 1: ML&LBL = −0.31 vs. HBL = +0.69; contrast 2: ML = −0.35 vs. LBL = +0.65), relatedness (unrelated = −0.17 vs. related = +0.83), and their interaction, random intercepts for subject and item, a by-subject random slope for relatedness, and a by-item random slope for group. Model comparison confirmed that the model including fixed effects was a better fit than the null model ($\chi^2(5) = 240.14$, $p < .0001$). There was a significant main effect of the first group contrast (ML/LBL vs. HBL), with increased ratings for high-proficiency bilinguals relative to the other two groups, which did not interact with relatedness (see Table 3 and Fig. 4). There was additionally a significant main effect of inherent relatedness with increased ratings for related items, and an interaction between relatedness and the second group contrast (ML vs. LBL). Planned pairwise comparisons of high-proficiency ($M = 2.33$, $SE = 0.25$) and low-proficiency bilinguals ($M = 1.35$, $SE = 0.12$) revealed significantly higher ratings by high-proficiency bilinguals for unrelated pairs ($z = 4.11$, $p < .001$). Though a similar pattern was observed for related pairs, the difference did not reach significance ($M = 8.39$, $SE = 0.14$ for high; $M = 7.82$, $SE = 0.26$ for low; z = 1.80, $p = .072$). Comparisons of high-proficiency bilinguals ($M = 2.33$, $SE = 0.25$) and monolinguals ($M = 1.83$, $SE = 0.22$) revealed significantly higher ratings by high-proficiency bilinguals for unrelated pairs ($z = 2.01$, $p = .045$), as well as related pairs ($M = 8.39$, $SE = 0.14$ for HBL; M=7.57, SE=0.24 for ML; $z = 2.46$, $p = .014$). Lastly, comparisons of low-proficiency bilinguals ($M = 1.35$, $SE = 0.12$) to monolinguals (M=1.83, SE=0.22) revealed that monolinguals trended towards higher ratings for unrelated pairs, but the difference did not reach significance ($z = -2.04$, $p = .082$). No difference was found between low-proficiency bilinguals ($M = 7.82$, $SE = 0.26$) and monolinguals ($M = 7.57$, $SE = 0.24$) for related pairs ($z = -0.36$, $p > .9$).[1]

Overall, results in this experiment are similar to Experiment 1 in showing increased semantic relatedness ratings among high-proficiency bilinguals compared to monolinguals. Moreover, we see a significant difference between the ratings of high- versus low-proficiency bilinguals, particularly for unrelated pairs, with low-proficiency bilinguals, along with monolinguals, giving lower semantic relatedness ratings than high-proficiency bilinguals. This finding supports our prediction that high bilingual proficiency is required before behavioral differences in concept relatedness judgments can be observed. The results are also consistent with the Hebbian Learning theory and the *Revised Hierarchical Model* in showing that as the L2 lexical-semantic links grow stronger, so do the associations between concepts through repeated spreading activations within and across levels of language representation.

Results in Experiment 2 additionally appear to suggest that the difference between monolinguals and bilinguals is not moderated by the inherent semantic relatedness of the stimuli pairs. Rather, the increased ratings among high-proficiency bilinguals were observed regardless of existing stimuli associations. On the other hand, while higher proficiency was generally associated with higher relatedness ratings, the difference between high- and low-proficiency bilinguals only reached significance for unrelated pairs, suggesting that the effect of bilingual experience may be more evident for concepts that are inherently unrelated.

4. Experiment 3a: conceptual replication of experiment 2 with linguistic stimuli

In Experiments 1 and 2, we demonstrated that experience with a greater diversity of phonological and lexical forms increases the perceived relationship between visually represented concepts. The trade-off of greater linguistic diversity, however, is often a reduction in the frequency of exposure to particular words or languages. Given that bilinguals split their time between different languages, their overall level of exposure to a given language is often lower than their monolingual counterparts' (Gollan & Acenas, 2004; Gollan, Montoya, & Werner, 2002). As such, while the conceptual representations of *goat* and *sleep* may be more likely to be coactivated by bilinguals as a result of latent cross-linguistic connections, the words "sheep" and "sleep," or "shan yang" (goat) and "mian yang" (sheep), may be more frequently coactivated by monolinguals of English and Mandarin, respectively. To the extent that

[1] We followed up on the effect of proficiency among bilinguals by replacing the categorical fixed effect (Low vs. High Bilingual) with a continuous measure of proficiency. Consistent with the primary analysis, we observe that there was a significant main effect of relatedness (*Estimate* = 5.89, SE = 1.25, $z = 4.73$, $p < .0001$), a significant main effect of proficiency (*Estimate* = 0.37, $SE = 0.18$, $z = 2.11$, $p = .035$), with higher ratings of semantic relatedness with greater proficiency, and no interaction between the two ($p > .05$).

Table 3
Experiment 2 multinomial logistic mixed effects regression.

Fixed Effect	Estimate	SE	z value	Pr(>|z|)
Intercept	−2.14	0.22	−9.86	<.001
ML & LBL vs. HBL	1.50	0.45	3.35	<.001
ML vs. LBL	−0.96	0.54	−1.78	0.074
Relatedness	5.51	0.34	16.02	<.001
ML & LBL vs. HBL: Relatedness	0.47	0.58	0.81	0.419
ML vs. LBL: Relatedness	−1.36	0.68	−1.99	0.049

Note: Results are on the logit scale.

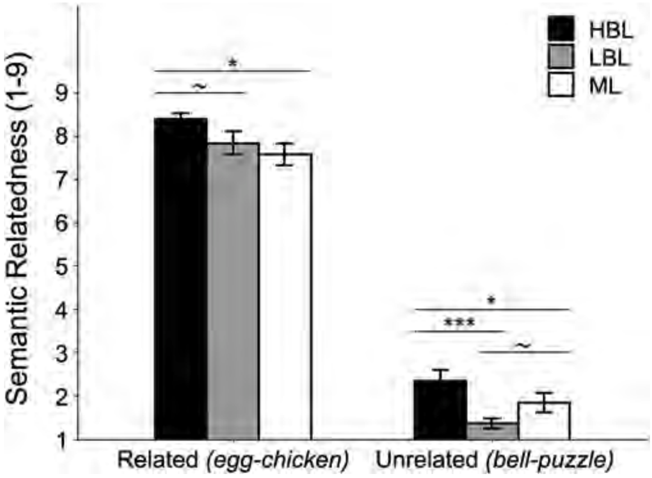

Fig. 4. Mean semantic relatedness ratings of related and unrelated picture pairs on the 1-9 scale (1: "not at all related"; 9: "completely related") by high- and low-proficiency bilinguals and monolinguals in Experiment 2. Error bars represent standard error.

more frequent exposure to particular word-pairs increases their perceived association, we might expect that the previously observed bilingual increase in semantic-relatedness may be reduced when concepts are directly cued by word-forms rather than pictures. This should particularly be the case for semantically related words, which are most likely to be encountered together in a given context. Experiment 3 therefore utilizes linguistic stimuli to investigate whether the effects of bilinguals' greater linguistic diversity are moderated by their likely reduction in language exposure. In Experiment 3a, written words are used in a semantic relatedness rating paradigm similar to Experiments 1 and 2. Experiment 3b (see Section 5) tests the same participants with verbal word stimuli in a semantic judgment task and additionally examines the neural correlates of the bilingual effect on semantic processing.

4.1. Methods

4.1.1. Participants

Twenty-three English monolinguals (mean age = 22.74 years; 7 males) and 22 Korean-English bilinguals (mean age = 21.62 years; 4 males) were tested. Participants completed the LEAP-Q and the Cognitive Battery of the NIH toolbox (Weintraub et al., 2013). Bilingual and monolingual participants did not differ in crystallized cognition, fluid cognition, composite cognition, dimensional change card sort, flanker task, or picture memory, *ps* > .05. Bilinguals had a high level of proficiency in both Korean and English, and did not differ from monolinguals on objective measures of English receptive vocabulary or oral reading recognition, *ps* > .05. Self-reported English proficiency was lower and English AoA was later among bilinguals compared to monolinguals (see Table 4).

Table 4
Experiment 3a participant language backgrounds, means and SDs.

Measure	Monolinguals	Bilinguals	
English AOA	0.11(5.48)	5.48 (2.93)	***
Korean AOA	–	0.90 (1.55)	
English Proficiency	9.74 (0.55)	8.70 (2.24)	*
Korean Proficiency	–	8.30 (2.16)	

Note: * = $p < .05$; *** = $p < .001$.

4.1.2. Stimuli

A total of 392 word pairs were constructed, including both concrete and abstract nouns. Each pair of English words (and their Korean translations) were phonologically unrelated to each other. Among these word pairs, 224 pairs were semantically related (e.g., "*nurse-doctor*"), selected from the Nelson Free Association Norms (Nelson, McEvoy, & Schreiber, 2004), and 168 word pairs were semantically unrelated (e.g., "*file-drink*"). To ensure that the semantically unrelated stimuli were indeed unrelated, twenty-two native speakers of English were recruited to rate the semantic relatedness of the unrelated word pairs on a scale from 0 ("not at all related") to 7 ("completely related"). The average semantic relatedness rating was very low, $M = 0.72$, $SE = 0.04$.

4.1.3. Procedure

All stimuli pairs were presented in an online questionnaire format using Google Forms. On each trial, two words were presented side-by-side on the computer screen and participants were asked to judge how related in meaning the two words were on a 0–7 scale, where 0 meant "not related at all" and 7 meant "highly related." The order of presentation was randomized for each participant.

4.2. Results and discussion

Semantic ratings were analyzed using multinomial logistic mixed effects regression, with fixed effects of group (contrast: monolingual = −0.49 vs. bilingual = +0.51), relatedness (unrelated = −0.57 vs. related = +0.43), and their interaction, random intercepts for subject and item, as well as a by-subject random slope for relatedness and a by-item random slope for group. Model comparison confirmed that the model including fixed effects was a better fit than the null model ($\chi^2(3) = 1040.40$, $p < .0001$). We found a significant main effect of relatedness (*Estimate* = 5.97, $SE = 0.23$, $z = 26.60$, $p < .0001$), no main effect of group (*Estimate* = 0.19, $SE = 0.25$, $z = 0.77$, $p = .441$), and a significant interaction between group and relatedness (*Estimate* = 0.85, $SE = 0.42$, $z = 2.04$, $p = .041$). Follow-up tests revealed that while bilinguals ($M = 0.65$, $SE = 0.14$) trended towards rating unrelated pairs as more related than monolinguals ($M = 0.34$, $SE = 0.06$), the difference did not reach significance ($z = 1.72$, $p = .086$), and there was no difference in how groups rated the related pairs ($M = 5.99$, $SE = 0.18$ for bilinguals; $M = 6.18$, $SE = 0.09$ for monolinguals; $z = -0.64$, $p = .52$). Including English proficiency as an additional fixed effect did not change the pattern and significance of the reported results for the primary model (i.e., significant main effect of relatedness and relatedness × group interaction, both $p < .05$). There were no main effects of English proficiency or group, nor a group × proficiency interaction (all $p > .05$), but there was a significant three-way interaction between relatedness, group, and proficiency (*Estimate* = 0.67, $SE = 0.07$, $z = 9.91$, $p < .0001$). Follow-up tests revealed no effects of group or proficiency for either related or unrelated pairs (all $p > .05$). See Fig. 5.

Unlike Experiment 2, which found significantly higher semantic relatedness ratings among bilinguals than monolinguals overall, the effect of bilingualism was substantially more modest in Experiment 3. This result is likely due in part to the different types of stimuli used in the two experiments. While Experiments 1 and 2 both utilized pictures to directly target semantic processing, Experiment 3 aimed to investigate how using word stimuli would affect rating outcomes. Unlike picture pairs, word pairs could become associated not only due to their inherent categorical similarities or the repeated coactivations of concepts (e.g., *sleep* and *sheep*), but also through repeatedly hearing and seeing their lexical forms co-occur in speech and text (the words "sleep" and "sheep"). It is possible that, because bilinguals split their time across two languages (Gollan & Acenas, 2004; Gollan et al., 2002) and have fewer opportunities than monolinguals to exercise the lexical-semantic links in each one, using English words instead of pictures may have dampened the effect of bilingualism on semantic associations.

This mechanism may also partly explain the second finding in this experiment, which is that instead of showing relatively similar effects of language group across the two relatedness conditions, the effect of bilingualism in Experiment 3 varied depending on the inherent semantic relatedness of the word pairs. Bilinguals trended towards rating inherently unrelated items (e.g., *wall-fruit*) as more semantically related, but no difference could be observed between bilinguals and monolinguals when it came to semantically related trials (e.g., "*nurse-doctor*"). Given that related words are especially likely to co-occur in a given text or conversation, lexical associations could have disproportionately boosted perceived similarities among monolinguals who may have had more frequent exposure to English word forms. If word forms are not directly activated (as in Experiments 1 and 2), the frequency of lexical co-activation may have a less significant impact on the perceived similarity of conceptual representations.

It should be noted, however, that because both bilinguals and monolinguals gave high ratings close to the top of the scale for the related pairs ($M = 5.99$, $SE = 0.18$ for bilinguals; $M = 6.18$, $SE = 0.09$ for monolinguals), the space to show potential increases in semantic relatedness was relatively limited. For the many instances when monolinguals selected 7 (completely related) on the scale, bilinguals would not have been able to select a higher number even if they did perceive stronger associations between highly related concepts (i.e. a ceiling effect). Experiment 3b therefore examined the neural correlates of the behavioral findings in order to explore the interaction between bilingualism and semantic relatedness using a less strictly bounded measure. Neural measures like event-related potentials (ERPs) are often more sensitive than behavioral measures in capturing nuances of processing in real time, and have revealed aspects of second-language processing that cannot be detected with behavioral measures alone (Thierry & Wu, 2007; Tokowicz & MacWhinney, 2005; Van Hell & Kroll, 2013).

5. Experiment 3b: neural correlates

Experiment 3b utilized event-related potentials (ERPs) to investigate potential differences in brain activity among bilingual and monolingual participants making behavioral "related" vs. "unrelated" judgments of word-pairs. We focused on the N400 component, which is a negative-going potential that peaks around 400 ms post-stimulus onset. This component is associated with semantic

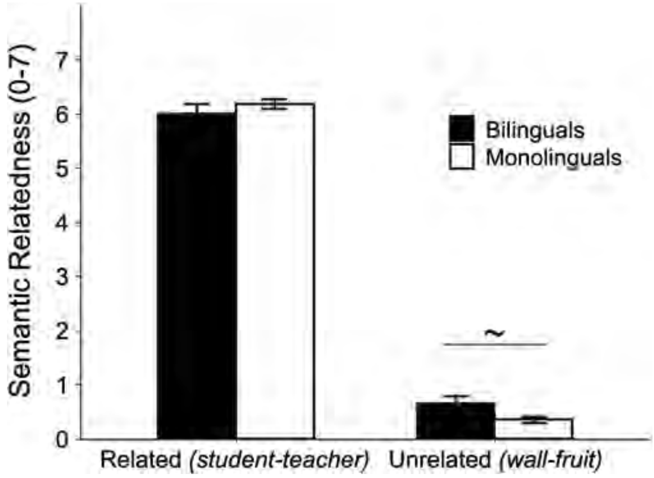

Fig. 5. Mean semantic relatedness ratings of related and unrelated word pairs on the 0-7 scale (0: "not related at all"; 7: "highly related") by bilinguals and monolinguals in Experiment 3a. Error bars represent standard error.

processing and can be reduced by semantic priming. Waveform amplitudes during the N400 time window are usually less negative when participants see semantically related versus unrelated stimuli, with the difference in amplitude across the related and unrelated conditions commonly referred to as the N400 effect (Kutas & Federmeier, 2000).

Because of significant individual variability in ERP amplitudes, absolute differences in N400 amplitudes can be difficult to meaningfully interpret. Experiment 3b therefore focused on comparing the N400 effect sizes (related – unrelated) across monolinguals and bilinguals. This comparison may help address some of the inconsistencies observed between Experiment 2 and Experiment 3a and shed light on whether the bilingual increase in perceived relatedness can only be seen for semantically unrelated words, or whether there is a more global effect that may have been obscured in Experiment 3a by bounded scales.

If the bilingual increase in semantic relatedness only extends to (or is significantly stronger for) semantically unrelated words, unrelated word-pairs should elicit N400 waveforms more similar to those of related word-pairs. In this case, bilingual participants' relative waveform amplitudes in the related compared to the unrelated condition (i.e., the N400 effect) should be smaller than those of monolinguals (i.e., a group × relatedness interaction). If, however, bilinguals perceive both related and unrelated pairs as more related, the magnitude of the N400 effect should be similar for bilinguals and monolinguals as the *relative difference* between related and unrelated waveform amplitudes would be comparable across groups.

5.1. Methods

5.1.1. Participants

The same participants from Experiment 3a were tested in Experiment 3b. In total, 26 English monolinguals (mean age = 22.56 years; 7 males) and 22 Korean-English bilinguals (mean age = 21.62 years; 4 males) were included in the behavioral data analyses.[2] See Table 5 for information about the participants included in the behavioral data analyses.

A subset of 16 monolinguals (mean age = 22.20 years; 3 males) and 15 bilinguals (mean age = 22.75 years; 3 males) were included in the ERP analyses after exclusions. Two monolinguals and one bilingual who were included in the behavioral analyses were excluded from the ERP analyses due to poor EEG data quality (i.e., no early components could be identified in the averaged ERPs). Additionally, seven monolinguals and six bilinguals were excluded from the ERP analyses because too few trials remained after artifact rejection ($n < 25$ per condition). One monolingual participant who judged a majority of the unrelated concept pairs incorrectly (64.29%) was identified as an outlier and excluded from the dataset. See Table 6 for information about the participants included in the ERP data analyses.

5.1.2. Stimuli

A total of 224 word pairs were included. Half of these word pairs were semantically related (e.g., "*jail-lock*", "*beef-cow*"); the same words were re-matched to create the semantically unrelated pairs (e.g., "*jail-cow*", "*beef-lock*"). Auditory stimuli were then recorded by a female native speaker of American English.

5.1.3. Procedure

Participants were prepared for EEG and tested individually in a quiet room. For each trial, participants heard two words with an interval of 400 ms. Upon seeing a black fixation cross that appeared simultaneously with the second word, participants indicated

[2] Three monolingual participants who were tested in Experiment 3b did not complete the semantic relatedness ratings in Experiment 3a.

Table 5
Experiment 3b participants in the behavioral analyses: language backgrounds, means and SDs.

Measure	Monolinguals	Bilinguals	
English AOA	0.1 (0.29)	5.48 (2.93)	***
Korean AOA	–	0.90 (1.55)	
English Proficiency	9.69 (0.64)	8.70 (2.24)	*
Korean Proficiency	–	8.30 (2.16)	

Note: * = $p < .05$; *** = $p < .001$.

Table 6
Experiment 3b participants in the ERP analyses: language backgrounds, means and SDs.

Measure	Monolinguals	Bilinguals	
English AOA	0 (0)	6.23 (2.70)	
Korean AOA	–		
English Proficiency	9.71 (0.64)	8.98 (1.21)	~
Korean Proficiency	–	8.87 (1.05)	

Note: ~ = $p < .1$.

whether the two words were semantically related by pressing one of two buttons on a handheld controller as quickly and as accurately as possible. The fixation cross disappeared after 1500 ms, and the inter-trial interval was 1000 ms (see Fig. 6). The corresponding "Yes" and "No" hands were counterbalanced across participants, and word pairs were randomized. Stimuli were presented using MATLAB (version 8.2, The MathWork Inc.) with PsychToolBox 3.0 (Brainard, 1997) on a Dell PC. Auditory sound files of words were played via two magnetically shielded speakers.

5.1.4. ERP recording

Electrophysiological data were recorded from 32 Ag/AgCl electrodes placed according to the extended 10–20 convention and referenced to the left mastoid online. Impedances were kept below 15 kΩ. All channels were amplified with a band pass of 0.01–100 Hz at a sampling rate of 500 Hz. After removing EEG components related to eye blinks, continuous EEGs were filtered with a band pass of 0.05–70 Hz and were re-referenced to the averaged mastoid reference. The EEGs were then segmented into epochs of 2200 ms, starting 200 ms before onset of the second word in each word pair. This analysis window was selected to accommodate processing time for auditory stimuli. Each epoch was baseline corrected for pre-stimulus activity. Epochs containing artifacts were discarded when the amplitudes exceeded 100 μV using a moving window of 200 ms in steps of 50 ms, or when simple voltage exceeded −120 μV or 120 μV in any channel.

5.1.5. ERP data analysis

After excluding trials with artifacts and missing responses, average ERPs were generated for each participant, electrode, and condition, and were filtered with a low pass filter of 30 Hz. ERPs were then computed by averaging EEG epochs from −200 to 2000 ms after stimulus onset. During epoching, baseline correction was applied in relation to 200 ms of pre-stimulus activity and individual averages were re-referenced to the average of the left and right mastoid electrodes. ERPs time-locked to the target word were visually inspected and the expected N400 component was identified. Eight centro-parietal electrodes (C3/4, CP1/2, P3/4, Cz, and Pz) were selected for ROI analyses based on previous literature, as the N400 has been shown to be stronger at these sites (Hoshino & Thierry, 2012; Kuipers & Thierry, 2010). Mean amplitudes of the N400 component were calculated and submitted to a 2 (group: monolinguals vs. bilinguals) * 2 (relatedness: related vs. unrelated) * 8 (electrode) ANOVA.

5.2. Results and discussion

5.2.1. Behavioral results

Participants' behavioral relatedness judgments for the word pairs were compared with our pre-established relatedness designations, and the proportions of "related" judgments were calculated. Based on our hypothesis, as well as on results from Experiments 2

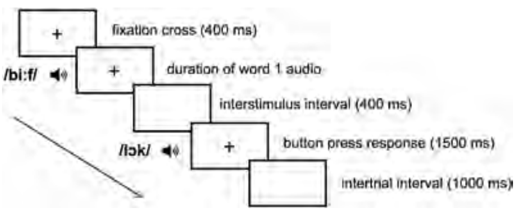

Fig. 6. A schematic representation of the procedure in Experiment 3b.

and 3a, we predicted that bilinguals would identify more stimuli pairs that were unrelated as related compared to monolinguals. Planned comparisons revealed that bilinguals categorized more unrelated pairs as related ($M = 7.34\%$, $SE = 0.01$) than monolinguals did ($M = 4.39\%$, $SE = 0.01$), and this difference trended toward significance, ($t(46) = -1.80$, $p = .079$). In contrast, the differences between groups in the proportion of incorrect judgments for related pairs was negligible ($t(46) = 0.30$, $p = .77$), with bilinguals and monolinguals making comparable numbers of related judgments (Bilinguals: $M = 88.43\%$, $SE = 0.02$; Monolinguals: $M = 89.11\%$, $SE = 0.02$).

When the data were submitted to a mixed model ANOVA with a between-subjects effect of group, and a within-subjects effect of relatedness, there was an effect of relatedness ($F(1, 46) = 3531.00$, $p < .001$), but neither the effect of group ($F(1, 46) = 0.65$, $p = .42$) nor the group*relatedness interaction ($F(1, 46) = 1.68$, $p = .20$) reached significance (see Fig. 7).

5.2.2. ERP results

Latencies. In order to determine the optimal time window for analyzing our primary variable of interest (i.e., ERP amplitude), we first examined the peak latencies of waveforms elicited by related and unrelated stimuli for monolinguals and bilinguals. Average ERP waveforms (time-locked to the presentation of related and unrelated word pairs) demonstrated a clear negative-going peak for both bilinguals and monolinguals around 600 ms post-stimulus onset (after onset of the second word in each word pair; see Fig. 8A). Peak latencies within 400–800 ms were calculated for both groups and averaged across 8 electrodes for each participant. The resulting values were then submitted to a 2 (group: monolinguals vs. bilinguals) * 2 (relatedness: related vs. unrelated) ANOVA. No significant main effect of group ($F(1,58) = 2.42$, $p = .13$) or relatedness ($F(1,58) = 2.43$, $p = .12$) emerged for peak latencies. The interaction between group and relatedness also did not reach significance ($F(1, 58) = 0.81$, $p = .37$). Planned comparisons revealed comparable peak latencies for bilinguals ($M = 590.51$ ms, $SE = 19.48$) and monolinguals ($M = 557.22$ ms, $SE = 18.86$) across conditions ($p = .229$).

The onset and duration of the N400 component was determined by calculating mean EEG amplitudes across the 8 electrodes in 50 ms intervals from 0 to 2000 ms after stimulus (second word) onset for both bilinguals and monolinguals. Similar moving window analysis methods have been adopted in prior work (e.g., Gunter, Friederici, & Schriefers, 2000; Hahne & Friederici, 2001), and are particularly useful in ERP studies where the onset and duration of effects are of importance, and parameters from previous studies are not applicable due to methodological differences. For monolinguals, a significant main effect of relatedness emerged during the 250–300 ms time window and lasted during all remaining time windows. For bilinguals, a significant main effect of relatedness emerged during the 400–450 ms time window and lasted through the 1350–1400 ms time window. Although on average, the N400 effect can be seen in both groups from 400 ms to 1400 ms post stimulus-onset, individual analyses revealed that the majority of bilingual participants displayed an earlier termination of the N400 effect. Therefore, 400–1200 ms post-stimulus onset was selected as the N400 time window for both participant groups in the analyses of ERP amplitudes.

This time window is noticeably later than the typical N400 window in other studies (e.g., 350–500 ms; Kutas & Hillyard, 1980, 1984), in part due to the auditory presentation of stimuli in the current experiment. The N400 effect has been observed in other studies with auditory presentations of semantically related and unrelated words (Holcomb & Neville, 1990, 1991; McCallum, Farmer, & Pocock, 1984), with some results suggesting that the auditory N400 effect could last longer than the visual N400 effect (Kutas, Van Petten, & Kluender, 2006, pp. 659–724). Furthermore, ERPs were time-locked to the onset of the second word in each stimuli pair. Therefore, the recorded time window included the length of time that the audio had to play before participants realized which word it was. The length of the second word in stimuli pairs varied, ranging from 330 ms ("*pen*") to 720 ms ("*organize*"), averaging 535.95 ms.

5.2.3. ERP results

Amplitudes. During the length of the N400 component (400–1200 ms after presentation of second word), participants' mean EEG

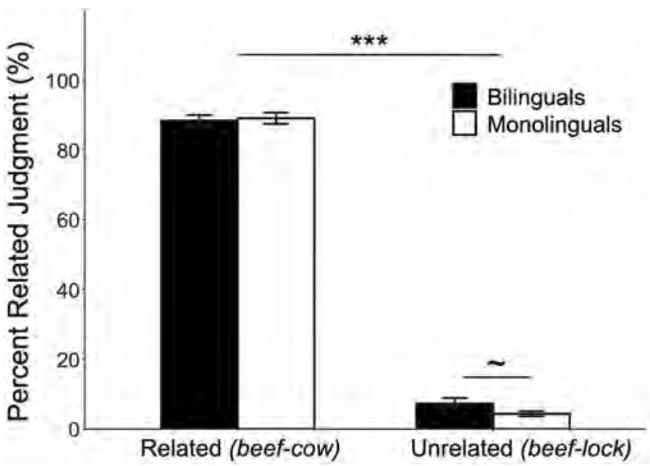

Fig. 7. Mean percentage of related and unrelated word pairs judged as semantically related by bilinguals and monolinguals in Experiment 3b. Error bars represent standard error.

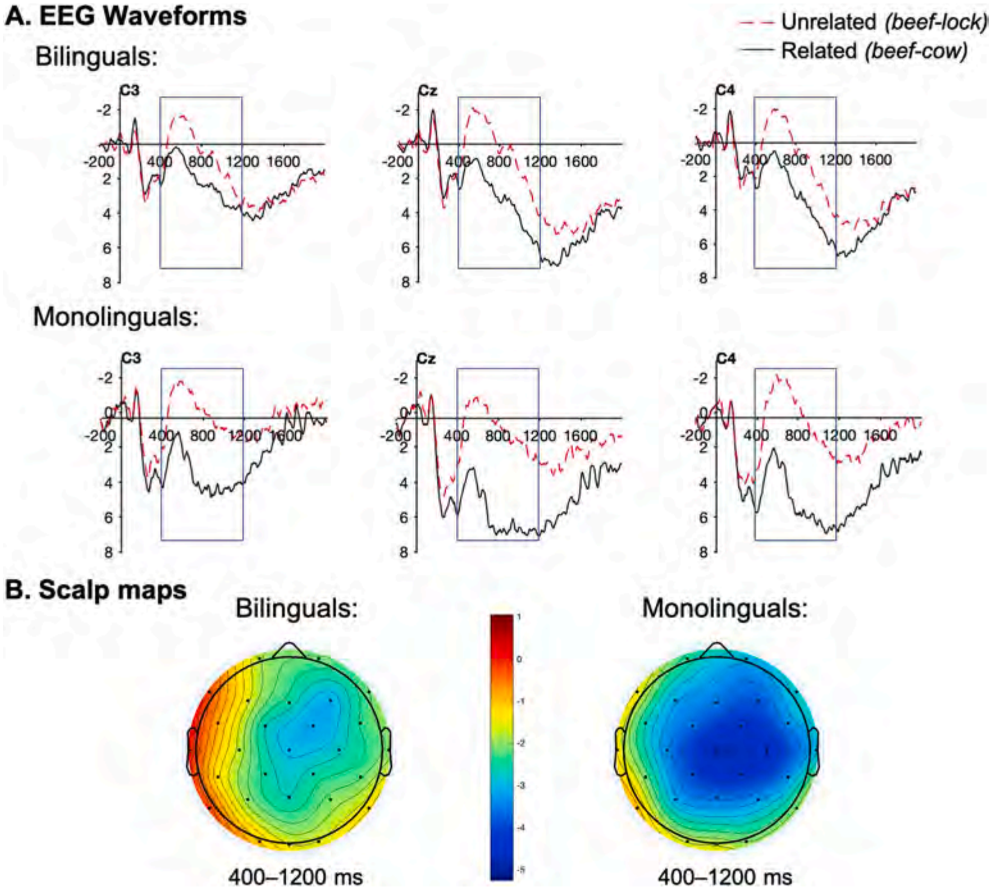

Fig. 8. (A) ERP waveforms recorded at centro-parietal sites in bilinguals (N = 15) and monolinguals (N = 16) in response to related and unrelated auditory word pairs. (B) Voltage scalp topography of bilingual and monolingual N400 difference waves (calculated by subtracting mean related amplitudes from mean unrelated amplitudes) from 400 to 1200 ms. The scale extends from −5 μV to 1 μV, with bluer shades representing a larger N400 effect. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

amplitudes at the 8 centro-parietal sites in each condition were calculated and submitted to a 2 (group: monolinguals vs. bilinguals) * 2 (relatedness: related vs. unrelated) * 8 (electrode) ANOVA. As expected, we found a significant main effect of relatedness ($F(1, 464) = 113.84$, $p < .0001$), with reduced negativity for related pairs ($M = 4.56$ mV, $SE = 0.21$) compared to unrelated pairs ($M = 1.43$ mV, $SE = 0.21$). The effect of group was not significant ($F(1, 464) = 1.39$, $p = .24$), with comparable amplitudes for bilinguals ($M = 2.82$ mV, $SE = 0.21$) and monolinguals ($M = 3.17$ mV, $SE = 0.20$) collapsing across the related and unrelated conditions. However, we found a significant group*relatedness interaction ($F(1, 464) = 6.44$, $p = .012$). Though follow-up tests revealed significant effects of relatedness for both bilinguals and monolinguals (both $p < .05$), the significant interaction reveals that bilinguals had a smaller N400 effect size (between-condition difference; $M = 2.39$ mV, $SE = 0.55$) than monolinguals ($M = 3.88$ mV, $SE = 0.53$). This N400 effect size difference is also readily observable on the topographic map of the scalp, calculated by subtracting mean related amplitudes from mean unrelated amplitudes (see Fig. 8B).

There was a significant main effect of electrode ($F(7, 464) = 4.56$, $p < .0001$). Pairwise comparisons of the electrodes suggested that the amplitudes were less positive (more negative) in C3 (1.49 μV), C4 (2.17 μV), and Cz (2.45 μV) than in CP1 (3.33 μV), P4 (3.33 μV), CP2 (3.40 μV), P3 (3.56 μV), and Pz (4.24 μV), with $ps < .05$ for all contrasts between C3/4 and the latter 5 electrodes. However, no relatedness*electrode ($F(7, 464) = 0.34$, $p = .94$) or relatedness*group*electrode interaction ($F(7, 464) = 0.037$, $p = .99$) was found, suggesting that the magnitude of the N400 relatedness effect was similar across the electrodes. Visual inspection of the scalp distribution also did not indicate differences in hemispheric lateralization of the effect.

5.2.4. Discussion

The N400 component is a negative-going peak in the EEG waveform around 400 ms post-stimulus onset, and the N400 effect is the EEG amplitude difference between conditions. Previous studies have found that a larger N400 component can be elicited with a semantically unexpected anomaly in sentences, and the N400 component can be reduced by semantic priming in processing both sentence and word lists. Therefore, an N400 effect (a significant between-condition difference) would be expected to arise when participants view or hear semantically related versus unrelated word pairs, with the amplitudes around 400 ms post-stimulus onset expected to be more negative for the unrelated stimuli pairs and less negative for the related pairs.

In the current study, bilinguals and monolinguals both displayed an N400 effect with comparable peak latencies. The presence of the N400 effect corresponds with previous studies on semantic processing for word pairs, but the latency results can be contrasted with studies testing bilingual populations that had acquired their second language later in life or had lower proficiencies in their second language. Late bilinguals with lower proficiency often display longer N400 latencies compared to monolinguals (Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Weber-Fox & Neville, 1996). With the relatively high-proficiency early bilinguals in the current study, this latency difference was not seen. Instead, we observed a smaller N400 effect in bilinguals than in monolinguals, suggesting that bilinguals processed unrelated and related concept pairs in a more similar way than monolinguals. This result alone could be interpreted as bilinguals either processing semantically related concepts as more "dissimilar" or processing semantically unrelated concepts as more "similar." The behavioral data across the three experiments, however, is more consistent with the interpretation that bilinguals judge concepts, especially semantically unrelated ones, as more related than monolinguals, corresponding with our hypothesis that bilinguals' denser connections in the word-form network contribute to closer semantic associations.

In contrast to Experiment 2, which showed a general increase in relatedness judgments among bilinguals, the behavioral results in Experiment 3 suggested that the effect of bilingualism may be limited to unrelated concepts. Though we considered the possibility of a ceiling effect, the fact that a similar asymmetrical effect was found for related and unrelated words using EEG may indicate that the different patterns observed between Experiments 2 and 3 are more likely due to the use of word versus picture stimuli. Based on the Hebbian principle that connections form between frequently co-occurring inputs, it would be reasonable to expect that repeated exposure to particular word-pairs in the same context could strengthen associations, not only between their conceptual referents, but between the word forms themselves. The use of word stimuli, then, could amplify the perceived relatedness of concepts by directly activating connections formed at both conceptual and lexical levels of representation. Furthermore, directly activating lexical nodes might highlight lexical or phonological feature overlaps which contribute to the perceived relationship between concepts. Though one could therefore predict that the use of linguistic stimuli would lead to a general increase in perceived relatedness, this is likely to be disproportionately the case for monolinguals who have a greater amount of exposure to the lexical forms of a single language. In other words, monolinguals' more frequent language exposure to lexical items could have counteracted the effects of bilinguals' more diverse language knowledge. Importantly, any consequences arising from the frequency of language exposure should be especially noticeable for inherently related words, which are more likely to be encountered together in the same context.

6. General discussion

The present study examined whether bilingual experience can change how strongly concepts are associated with each other in a person's mind. Two behavioral experiments and one ERP experiment compared the strength of bilinguals' and monolinguals' semantic associations. In Experiment 1, Spanish- and English-speaking bilinguals rated picture pairs as significantly more related in meaning than English monolinguals. In Experiment 2, we examined the effects of bilingual proficiency and inherent stimuli relatedness, and found that high-proficiency bilinguals of Spanish and English gave higher ratings of both related and unrelated stimuli than monolinguals and low-proficiency bilinguals. Experiment 3 used behavioral and neural measures to assess whether the effect of bilingualism generalizes to linguistically represented concepts and a different language population. Korean-English bilinguals and English monolinguals judged the semantic relatedness of related and unrelated English word pairs in both a behavioral rating task and an ERP experiment with yes/no button press trials. Behavioral ratings trended in the predicted direction, with a bilingual increase in perceived semantic relatedness for unrelated, but not related pairs. ERP results showed significantly smaller N400 effects for bilinguals, which suggests that bilinguals processed unrelated word-pairs more similarly to related word-pairs than monolinguals did. Together, the findings across all three experiments suggest that bilingualism increases perceptions of semantic relatedness, but that this may be selectively the case for unrelated concepts when they are represented linguistically.

The three experiments included in this investigation utilized different stimuli, testing procedures, and participant groups, which allowed us to examine how well the phenomenon generalized to different contexts and populations. When measuring semantic associations, concept pairs were presented as either black-and-white line drawings (Experiment 1 and Experiment 2), or as visual (Experiment 3a) or auditory (Experiment 3b) words. Because words more directly activate linguistic representations than pictures do, we may have expected that judgments of similarity for linguistically represented concepts would be especially influenced by phono-lexical features and the density of language networks. However, as we saw from Experiment 3, bilinguals' lower proficiency in the test language, as well as reduced exposure to lexical items in each of their languages compared to monolinguals may work against the hypothesized effect of network density, ultimately attenuating the bilingual increase in semantic relatedness judgments that was robustly observed with picture stimuli in Experiments 1 and 2. These findings demonstrate that the effect of bilingualism on semantic associations is sensitive to both the mode of presentation as well as the individual's level of proficiency in their two languages. Despite variability in the strength of the effect depending on stimulus type, experiment procedure, or bilingual population, we consistently found that extensive bilingual experience can change semantic associations. The influence of bilingualism on semantic associations therefore appears to be relatively robust and can be detected with or without overt language activation to varying degrees. Future studies could more systematically examine the boundaries of the effect, such as through direct comparisons of word and picture stimuli with bilinguals who have comparable proficiency to monolinguals, as well as with bilingual populations who speak languages that vary in their degree of typological or cultural distance. The effect of other stimulus characteristics on bilingual semantic judgment such as frequency, concreteness, and imageability can also be explored in future studies.

The current findings support our hypothesis that through acquiring a second language, bilinguals, especially those with high mastery of the second language, may develop more links between words, and in turn, concepts, than monolinguals. Returning to our counting goats example, these additional associations could include direct linguistic associations from a second language (e.g., the phonological link of "*mian yang*" (sheep) and "*shan yang*" (goat) in Mandarin), as well as new cross-linguistic associations created on the basis of existing associations in each language (e.g., "*sleep-goat*", with "*sheep*" as the mediating node between the phonological link of "*sleep-sheep*" in English and the phonological link of "*sheep-goat*" in Mandarin). Additionally, though our example emphasizes phonological associations, lexical connections such as shared grammatical gender or orthography may also affect semantic associations in similar ways.

Existing connectionist theories of language processing and bilingualism propose a connected model of language in which the structure of the lexical and phonological levels influence conceptual level associations. Our finding that bilinguals have increased semantic associations, with the increase potentially stemming from a greater diversity of lexical and phonological connections between individual concept nodes, is consistent with models of language processing that include bidirectional cross-level activations. The fact that bilinguals' denser lexical and phonological connections result from having two language systems also indicates a shared lexical and phonological space for bilinguals' two languages, as depicted in models of bilingual language processing like *BLINCS* (Shook & Marian, 2013). Furthermore, results from Experiment 2 provide support for the *Revised Hierarchical Model* of bilingual language processing (Kroll & Stewart, 1994) in that conceptual connections to L2 lexical items may first be mediated through L1, and gradually grow stronger as bilinguals' L2 proficiency increase.

Established models and empirical findings provide the basis for our hypothesis that denser lexical and phonological networks lead to bilinguals' closer semantic associations. Our future efforts will focus on building a computational model of bilingual language processing that allows for precise simulations of how cross-linguistic lexical and phonological links may affect semantic organizations. Such a model will extend existing bilingual connectionist models like *BLINCS* (Shook & Marian, 2013) to accommodate bilinguals' semantic relatedness judgments. Currently, normative databases for semantic relatedness and co-occurrence exist in English and several other languages including Spanish (e.g., Barrón-Martínez & Arias-Trejo, 2014) and Dutch (e.g., De Deyne & Storms, 2008), but monolingual-bilingual differences in semantic associations have not been studied.

Future research may additionally explore the relationship between bilinguals' tendency to identify meaningful relationships between seemingly unrelated items and prior work demonstrating greater creativity and divergent thinking for bilinguals compared to monolinguals (Ricciardelli, 1992). Proposed explanations have included higher selective attention (Kharkhurin, 2011), greater tolerance of ambiguity (Ricciardelli, 1992), and a richer socio-cultural toolbox to draw from when faced with a problem (Lee & Kim, 2011). Factors underlying bilinguals' increased creativity may have contributed to the bilingualism effect observed in this study, and creative insights may emerge from the connectivity of the language system. In order to isolate the influence of linguistic knowledge from potential confounds such as cultural experiences, frequency of language exposure, and non-linguistic abilities, future investigations of semantic relatedness and creative thinking can benefit from the use of artificial language stimuli representing novel concepts.

Although many questions remain regarding the complex relationship between language and thought, we conclude that bilingual experience can increase the density of lexical-semantic networks, with measurable consequences for semantic associations.

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CRediT authorship contribution statement

Siqi Ning: Writing - original draft, Writing - review & editing, Data curation, Formal analysis, Visualization, Conceptualization. **Sayuri Hayakawa:** Conceptualization, Writing - review & editing, Data curation, Formal analysis, Visualization. **James Bartolotti:** Data curation, Formal analysis, Visualization, Methodology, Writing - original draft. **Viorica Marian:** Conceptualization, Resources, Funding acquisition, Supervision, Project administration, Methodology, Writing - review & editing.

Declaration of competing interest

None.

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