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Cognitive and Linguistic Predictors of Bilingual Single-Word Translation

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Abstract

One of the advantages of being bilingual is the ability to translate from one language to the other. From language learners to professional interpreters, many different types of bilinguals engage in translation in their daily lives. How successful they are, however, depends on a wide range of factors. The current study aimed to identify the cognitive and linguistic variables that predict how quickly and accurately bilinguals are able to translate single words. Eighteen Chinese-English bilinguals listened to words in their second language (L2 English) and verbally translated them into their native tongue (L1 Chinese). We observed that translation performance was predicted by factors related to language background, such as second language competence and language exposure, as well as domain-general cognitive abilities, such as inhibitory control. Translation performance was additionally influenced by features of the source language, such as word frequency, neighborhood density, and bi-gram/bi-phone probability. By examining factors relating to language experience, cognitive ability, and linguistic input, we shed light on the dynamic interaction that is required among multiple variables for successful translation.

Keywords: single word translation, bilingualism, proficiency, cognitive ability

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1 Introduction

Over 7,000 languages are spoken around the world today (Ethnologue, 2018). As society becomes increasingly globalized, the ability to transcend linguistic barriers becomes ever more necessary for activities ranging from engaging in international diplomacy to enjoying foreign language films. Indeed, some estimates suggest that half, if not more, of the world's population speaks at least two languages (Grosjean, 2010). As a result, there has been substantial research dedicated to understanding how individuals acquire foreign languages (e.g., Bartolotti & Marian, 2017; Birdsong, 2009; Kempe & Brooks, 2011), how multiple languages are represented and controlled (e.g., Green, 1998; Kroll & Stewart, 1994; Marian & Spivey, 2003), as well as how multilingualism impacts the cognitive architecture (e.g., Bialystok, 2001; Costa, Hernández, & Sebastián-Gallés, 2008; Luk, Bialystok, Craik, & Grady, 2011; Shook & Marian, 2013). Relatively less attention in the bilingualism literature has been directed to the factors that influence translation from one language to the other – this, despite the fact that almost every bilingual engages in some translation (Malakoff & Hakuta, 1991), including toddlers as young as three years-old (Harris & Sherwood, 1978). Furthermore, the consequences of *incorrect* translations can range from mild social embarrassment (Stampler, 1997) to political (Freeland, 2018) and financial catastrophe (Nakata, 2012). Given the ubiquity and importance of translation in an increasingly multilingual world, there is a need to better understand the individual and contextual variables that influence how effectively a message can be transmitted from one language to another. To shed light on this issue, the present study examines how single-word translation is affected by the cognitive abilities and language backgrounds of the translators, as well as by the word properties and linguistic features of the language itself.

Translation is sometimes regarded as a special ability that is relevant only to trained professionals (Whyatt, 2012). Similarly, much of translation research has focused on highly skilled experts, such as simultaneous interpreters. Simultaneous interpretation requires extensive linguistic knowledge and cognitive resources, as interpreters must concurrently comprehend one language while producing another. It is therefore perhaps unsurprising that working memory has been identified as a major predictor of performance among this specialized population (Christoffels, de Groot, & Waldorp, 2003; Lin, Lv, & Liang, 2018; Macnamara & Conway, 2018; Tzou et al., 2012). Other factors including L2 proficiency (Tzou et al., 2012), translation expertise (Garcia et al., 2014), and the ability to inhibit distractors (Timarová et al., 2014) have also been linked to interpreting performance. Simultaneous interpreters additionally often have larger working memory spans (Babcock & Vallesi, 2017; Bajo, Padilla, & Padilla, 2000; Christoffels, de Groot, & Kroll, 2006; Garcia, 2014; Tzou et al., 2012), better cognitive flexibility (Garcia, 2014), and higher language processing efficiency (Garcia, 2014; Tzou et al., 2012) compared to even highly proficient, but untrained bilinguals. Though these enhanced linguistic and cognitive abilities are essential for the arduous task of simultaneous interpretation, most bilinguals do not experience the same level of demand or pressure when engaged in more common translation activities. In order to more fully characterize the broad spectrum of challenges and abilities associated with translation, our goal is to examine the functions and factors that predict untrained bilinguals' performance on the most basic task of translating single words.

While the translation ability of untrained bilinguals is not often the primary focus of empirical research, translation tasks are frequently used as a tool to examine other aspects of bilingual cognition, such as lexical representations and memory (e.g., Chen & Leung, 1989; de

Groot & Poot, 1997; Kroll & Stewart, 1994; Potter, So, Eckardt, & Feldman, 1984). For instance, Potter et al. (1984) used a translation task to investigate whether L1 and L2 words have direct connections to each other at the lexical level (e.g., “cat” ←→ “gato”), or whether they are connected through their underlying shared concept (e.g., “cat” ← → *concept of cat* ←→ “gato”). The authors argued for the latter based on the finding that participants were faster at naming pictures in their L2 than translating L1 words into L2. As the byproducts of this type of research, several factors have been shown to influence translation ability. For example, cognitive abilities, such as working memory, can impact translation accuracy (Kroll, Michael, Tokowicz, & Dufour, 2002). Basic language processing abilities, such as those assessed by word identification and lexical decision speed, are predictive of translation speed (Malakoff & Hakuta, 1991; Prior, Kroll, & MacWhinney, 2013). Properties of the language, such as word frequency (de Groot et al.,1992,1994), cognate status (Christoffels, de Groot, & Kroll, 2006; de Groot et al., 1992, 1994; Macizo & Bajo, 2006), contextual availability (how easy it is to think of a context in which a word can be used), word class (de Groot et al., 1992,1994; Van Hell & de Groot, 1998), and lexical ambiguity (Macizo & Bajo, 2006; Michael, Tokowicz, Degani, & Smith, 2011; Prior et al., 2013) have all been associated with translation performance.

These findings suggest that translation performance is affected by cognitive abilities, as well as linguistic factors, which include the language experience of the translators and the characteristics of the language to be translated. However, to our knowledge, no existing study has investigated all three simultaneously. The current study serves as a starting point for examining how translation performance is jointly influenced by language experience, cognitive abilities, and word properties by using a single-word backward translation task (L2 to L1). Next, we describe variables from each of these categories in more detail.

1.1 Language Experience

One of the most reliable factors affecting translation performance is language proficiency. Higher proficiency in L2 is predictive of better performance (i.e., shorter reaction times, or fewer errors and omissions, e.g., Christoffels et al., 2006; de Groot & Poot, 1997). While it may be most intuitive to expect translation ability to depend on L2 proficiency, L1 proficiency may also play a role. This is because translation requires bilinguals to both comprehend the *source* language and produce the *target* language, making proficiency in both languages potentially relevant. As such, we expected that higher proficiency in both L1 and L2 should be predictive of better translation ability.

Another factor often associated with L2 proficiency is L2 age of acquisition (AoA). While in many cases, AoA is negatively correlated with proficiency (Flege, Yeni-Komshian, & Liu, 1999), it may have distinct contributions to translation performance. Indeed, AoA has been shown to impact related processes such as lexical and semantic access (e.g., Canseco-Gonzalez et al., 2010; for review, see Hernandez & Li, 2007), even after controlling for proficiency (Silverberg & Samuel, 2004). Relative to languages acquired later in life, earlier languages are often more closely integrated and share more common cortical areas with the native tongue (e.g., Kim, Relkin, Lee, & Hirsch, 1997; Perani et al., 2003). As such, in addition to the potentially higher levels of proficiency associated with earlier acquisition, a closer link between bilinguals' two languages could result in faster retrieval of the translation equivalents, potentially due to more frequent co-activation (Canseco-Gonzalez et al., 2010). Thus, we expected that earlier L2 AoA should improve translation performance.

Lastly, in addition to the age of initial language exposure, current exposure to L1 and L2 may influence translation performance. Evidence suggests that increased exposure to L2 can improve performance on L2 comprehension and production, while reducing verbal fluency in L1 (Linck, Kroll, & Sunderman, 2009). Given that translation requires access to both languages, L1 and L2 exposure may have conflicting effects on backwards translation performance. Increased L2 exposure would likely facilitate comprehension of the L2 source word, while decreased L1 exposure may inhibit retrieval of the L1 target word. In summary, we collected measures of L1 and L2 proficiency, L2 age of acquisition, and L1 and L2 current exposure in order to assess the influence of language experience on performance during backward translation (L1 Mandarin to L2 English).

1.2 Cognitive Abilities

Successful translation depends on not only domain-specific linguistic knowledge, but also on domain-general cognitive functions. Even the simplest task of translating single words involves numerous stages of processing: the translator must identify the word in the source language, search within the mental lexicon while remembering the word to be translated, and produce the translation equivalent in the target language. Coordinating among these steps likely depends on general cognitive abilities in addition to knowledge acquired through language experience. For instance, working memory has been shown to influence the types of translation errors people make (Tokowicz, Michael, & Kroll, 2004), and to affect the resolution of translation ambiguity (Prior et al., 2013). Furthermore, simultaneous interpreters have been shown to have better working memory than college teachers despite similar levels of language proficiency (Christoffels et al., 2006). This suggests that translating may recruit and even improve working memory under highly challenging conditions. However, the role of working memory is less clear for simpler translations that are required for everyday life. The current study thus examines the effect of working memory in a single-word translation task while controlling for other cognitive abilities that may serve distinct functions.

One potentially relevant skill is inhibitory control. There is now substantial evidence that bilinguals activate both languages during comprehension even when only one is in use (e.g., Marian & Spivey, 2003; Shook & Marian, 2012), and yet intrusions from the non-target language during production are rare (Gollan, Sandoval, & Salmon, 2011). Research suggests that bilinguals are able to seamlessly utilize only the intended language by recruiting inhibitory control mechanisms to resolve linguistic conflicts (Abutalebi & Green, 2007; Kroll, Bobb, Misra, & Guo, 2008). The potential benefits for translation, however, are less obvious, as translating requires the use of both languages and excess inhibition could prove to be counterproductive. And yet Michael et al. (2011) found evidence that greater inhibitory control is also associated with improved translation accuracy and speed. The authors propose that rather than directly contributing to the translation process, greater inhibitory control may promote language learning, which could subsequently facilitate translation. The present study allows us to assess this possibility by examining the effect of inhibitory control after accounting for differences in language proficiency.

Lastly, we investigated the relationship between translation performance and non-verbal intelligence. Relatively little is known about the effect of intelligence on language learning, let alone language translation. There is some indication that intelligence may have a modest effect on language learning (Pishghadam & Khajavy, 2013), and a weak effect on language usage skills (Genesee, 1976). As both translation and intelligence have been linked to memory encoding and retrieval (e.g., Engle, Laughlin, Tuholski, & Conway, 1999; Herlitz & Yonker, 2002; Prior et al., 2013; Tokowicz et al., 2004), there is reason to think that intelligence may be positively associated with translation ability. It should be noted that intelligence as a variable has a controversial history in bilingualism research due to the fact that both intelligence and bilingualism are difficult to define and measure (Baker, 1988). With this in mind, we utilized a validated comprehensive language experience and usage questionnaire (i.e., LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007), as well as a standardized measurement of intelligence (i.e., Wechsler Abbreviated Scale of Intelligence, WASI; Wechsler, 1999) in order to explore the potential relationship between intelligence and linguistic skills. By examining the joint effects of cognitive abilities, such as intelligence, and language experience, such as proficiency, we can gain better insight into the factors that contribute to individual differences in the ability to translate.

1.3 Word properties

Beyond differences across individuals, the ease and quality of translations vary as a function of the language itself. Previous studies have found that translating words of greater length and lower frequency results in longer reaction times and more errors than shorter or more frequent words (de Groot et al., 1992; 1994). In addition to word frequency and word length (both phonological and orthographic), we also examine the impact of phonological and orthographic neighborhood sizes. In auditory word recognition tasks, phonological and orthographic neighborhood sizes (that is, how many phonologically or orthographically similar words there are) have been found to have opposite effects on recognition performance. Increased orthographic neighborhood size facilitates auditory word recognition. This is because words with orthographically dense neighborhoods tend to have more conventional and consistent mappings between how a word is written (e.g., “wipe”) and how it sounds (e.g., /waɪp/) relative to those with sparser orthographic neighborhoods (e.g. “type” and /taɪp/). Greater consistency between orthography and phonology may make it easier to identify the phonemes of a spoken word, leading to faster recognition. On the contrary, increased phonological neighborhood size hinders auditory word recognition (i.e., more errors and slower response times, e.g., Ziegler, Muneaux, & Grainger, 2003). This is because words with phonologically dense neighborhoods tend to induce greater competition from similar sounding words, compared to words with sparser phonological neighbors. Greater competition leads to prolonged recognition time of auditory words. We may expect similar effects for translation, with facilitative effects of orthographic neighbors and inhibitory effects of phonological neighbors. However, because the two variables are often correlated in natural language (Peereman & Content, 1997), we may observe that the inhibitory effect of phonological density may overwhelm the facilitative effect of orthographic density.

Lastly, we examine the possible influences of bi-phone and bi-gram probabilities on translation. Bi-phone, or phonotactic, probability refers to the likelihood of a given phonological sequence occurring in a given language (Vitevitch & Luce, 2004). For example, the probability of the phonological sequence /pa/ occurring in English is higher than /za/. Although bi-phone probability is often correlated with neighborhood density, it also has distinct influences on lexical processing (Pylkkänen, Stringfellow, & Marantz, 2002). For instance, Vitevitch and Luce (1999) have provided evidence that bi-phone probability facilitates spoken word recognition, most likely through sublexical activation, while, as noted previously, phonological neighborhood density inhibits recognition. Indeed, the authors find that increased bi-phone probability facilitates recognition specifically for non-words that do not allow for competing inhibitory effects at the lexical level. Given that high bi-phone probability usually corresponds to high neighborhood density, real words did not show the bi-phone facilitation effect. As the present study also used real words, we may similarly expect bi-phone and bi-gram probability to be overshadowed by the effects of phonological and orthographic neighborhood size. However, if distinct effects of bi-phone and bi-gram probability are observed, it would provide evidence that bilinguals are sensitive to fine-grained frequency information, indicating an effect that goes beyond the level of whole word frequency.

In summary, the current study examined bilinguals' performance in a backward translation task (from L2 to L1) in order to observe the effects of factors related to language experience, cognitive abilities, and word properties.

2 Method

2.1 Participants

Nineteen Chinese-English bilinguals residing in the U.S. participated in the present study. One participant was excluded for performing over one standard deviation below the mean for IQ distribution a standardized intelligence test (Wechsler Abbreviated Scale of Intelligence, WASI, score = 78; Wechsler, 1999). The remaining bilinguals (6 males, 12 females) ranged in age from 18-32, had an average IQ score of 118 (range: 109-129, SD = 5.91, from 13 participants[1]), and had normal or corrected-to-normal vision. On average, participants had 15.85 years of education (range: 12-23, SD = 4.15). They completed the *Language Experience and Proficiency Questionnaire* (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007), which revealed an average self-rated proficiency (across reading, speaking, and understanding) of 9.22 out of 10 (range: 6-10, SD = 1.19) for Chinese (L1) and 8.04 (range: 5-10, SD = 1.76) for English (L2). English proficiency was marginally lower than Chinese proficiency, $p = .06$. While none of the participants were born in the U.S., three of them immigrated to an English-speaking country

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[1] Note that not every participant contributed data for the cognitive individual difference measures, and so the relevant analyses were restricted to the 11 out of 18 participants with complete data sets.

around the age of 2. The mean age of moving/immigrating to an English-speaking country was 14.5 years (range: 2-30, SD = 9.5) and the average age of English acquisition was 7.11 years (range: 3-13, SD = 3.41).

2.2 Materials

Translation task: Stimuli included 120 monosyllabic English words whose translations could be orthographically represented by a single Chinese character (see Appendix). These English words were recorded by a female Mandarin-English bilingual. Linguistic properties of these stimuli are described in the Word Properties section.

Language Experience: Participants' language histories and profiles were assessed using the LEAP-Q. Participants were asked for their self-rated proficiency (on a 0-10 scale in which "0" indicates "none" and "10" indicates "perfect") on reading, speaking, and listening comprehension in both Chinese (L1) and English (L2). Participants also reported the age of acquisition and current exposure for each language.

Cognitive Abilities: Non-verbal intelligence was measured by performance subtests of the *Wechsler Abbreviated Scale of Intelligence* (WASI). Verbal working memory was assessed using the digit repetition subset of the *Comprehensive Test of Phonological Processing* (CTOPP; Torgesen, Wagner, & Rashotte, 1999). Finally, inhibitory control was indexed by the Simon Task (Simon & Small, 1969). In the Simon Task, participants were asked to respond to the color of a rectangle on the screen by pressing two keys located on the left or right side of the keyboard. The rectangle could appear on the same side of the assigned response key (congruent trials), the opposite side of the assigned response key (incongruent trials), or at the center of the screen (neutral trials). The inhibitory control score was calculated by subtracting mean reaction time on neutral trials from mean reaction time on incongruent trials. Lower scores (i.e., smaller response time differences between neutral and incongruent conditions) thus indicated better inhibitory control function.

Word Properties: For each English word, we obtained frequency, orthographic and phonological word-length, as well as bi-phone and bi-gram probabilities from the *Cross-Linguistic Easy-Access Resource for Phonological and Orthographic Neighborhood Densities Database* (CLEARPOND database, Marian, Bartolotti, Chabal, & Shook, 2012). These English words had an average orthographic length of 4.05 (range: 3-7, SD = 0.88) and an average phonological length of 3.21 (range: 2-5, SD = 0.68). The mean frequency of these word was 261.45 per million words (range: 3.35-3793.04, SD = 552.26). The average orthographic and phonological neighborhood sizes were 12.81 (range: 1-39, SD = 8.10) and 24.42 (range: 5-56, SD = 12.70) respectively. The mean bi-gram and bi-phone probabilities were 0.008 (range: 0.00055-0.022, SD = 0.004) and 0.004 (range: 0.0001-0.013, SD = 0.003).

2.3 Procedure

After obtaining informed consent, all participants were administered the following assessments in the following order: 1) LEAP-Q for language experience; 2) WASI for non-verbal intelligence; 3) CTOPP for verbal working memory; 4) Simon Task for inhibitory control; and 5) the translation production task. In the translation production task, stimuli were presented via MATLAB/PsychToolBox (MathWorks Inc., Natick, MA; Brainard, 1997). Every trial started with a 500 ms blank white screen, followed by a 200 ms presentation of a black fixation-cross at the center of the screen. After the fixation-cross disappeared, each English word was played through two speakers, and participants were asked to produce Chinese translations as quickly and accurately as possible into a microphone which recorded their responses. The response time measure was triggered at the onset of each English word and ended by the onset of participants' responses. At the end of each trial, participants were asked to press the space bar when they were ready for the next trial. Each session lasted approximately two hours.

2.4 Data Coding

Translation responses were transcribed and coded by a Mandarin-English bilingual. A response was coded as correct when it shared a character with the predetermined Chinese translation (see Appendix). Out of the total 2160 trials, 10 were excluded due to software failures. Thus, a total of 2150 trials (1312 trials for cognitive ability predictors) were included in the accuracy analysis. Of the remaining trials, 408 were marked as incorrect due to missing or wrong responses, resulting in an overall accuracy rate of 81.02%. Among the 1742 correct trials, 86 were excluded due to missing reaction time measures (technical issues), 39 due to imprecise response time onsets (e.g., sometimes participants made hesitation sounds like “uh” before producing the translations), and 129 as a result of reaction times longer than 3000 ms or shorter than 500 ms. A total of 1488 trials (961 trials for cognitive predictors) were included in the response time analysis.

2.5 Data Analysis

For the initial analyses, average accuracy and response time were calculated for each participant and word. We then conducted three sets of bivariate correlations for language experience, cognitive ability, and word property variables to assess their relationships to accuracy and reaction time.

Next, we examined the variance explained by individual variables using linear mixed-effect models with by-trial accuracy and reaction time as the dependent variables. Given that many of the variables were correlated, we conducted separate factor analyses for the language experience and word property measures (with principal component extraction and varimax rotation) in IBM SPSS Statistics 20. Three separate factors were identified for the language experience measures that we label L2 competence, L1 competence, and exposure (see Table 1 for factor loadings. Loadings that were smaller than 0.4 were omitted).

Table 1. Factor loadings among language experience predictors.

Original variables	Component 1 (L2 Competence)	Component 2 (L1 Competence)	Component 3 (Exposure)
L1 speaking		0.918	
L1 understanding		0.939	
L1 reading		0.929	
L1 current exposure			0.917
L2 speaking	0.897		
L2 understanding	0.922		
L2 reading	0.866		
L2 current exposure			-0.928
L2 age of acquisition	-0.817		

In the factor analysis for word property measures, phonological length was removed because it loaded similarly onto two components. Because word frequency did not load strongly on any of the factors (loading = 0.496), we included it as a separate variable in the mixed effects model. Dropping frequency from the factor analysis improved the total explained variance from 63% to 73%. In addition to word frequency, two factors were identified for the word property measures that we label lexicality (i.e., how many words sound/are written similarly to the target word) and sublexicality (i.e., how common the sound/letter combinations are in the target word; see Table 2 for factor loadings. Loadings that were smaller than 0.4 were omitted).

Table 2. Factor loadings among word property predictors.

Original variables	Component 1 (Lexicality)	Component 2 (Sublexicality)
Orthographic length	-0.784	
Orthographic neighborhood size	0.924	
Phonological neighborhood size	0.829	
Bi-gram probability		0.793
Bi-phone probability		0.806

Using the loadings from each of the two factor analyses, we created composite measures using Bartlett scores generated by SPSS. Bartlett scores are produced by using maximum likelihood estimates and thus are unbiased estimates of the true factor scores (Hershberger, 2005). No factor analysis was run for the cognitive measures as there were only three measures to begin with.

As a model including all factors failed to converge, we began by running separate mixed effects models for each of the three components (language experience, cognitive ability, and word property) using the lme4 package (version 1.1-11, Bates, Mächler, Bolker, & Walker, 2014) in the R environment (version 3.2.3, R Core Team, 2015). For each component, we ran two separate models for each of the dependent variables of accuracy and reaction time, including both fixed and random effects. For language experience, we entered the variables identified by the factor analysis (e.g., L1 competence, L2 competence, and exposure) as well as all interaction terms as fixed effects. In the case of cognitive ability, we entered the raw, centered scores of the three measures (IQ, working memory, and inhibitory control) and all interaction terms as fixed effects. For word properties, we entered the two variables identified by the factor analysis as well as log transformed word frequency and all interaction terms as fixed effects. All models included random intercepts for both item and subject. In addition to examining variables within each of the three domains, we ran a series of model comparisons (ANOVA function) and used the AIC (Alkaike's information criteria) to identify the four best-fitting models that included variables from two different domains. The specific structures and outputs of each model are presented in the Results section. As these models were designed to test the interaction between different domains, only significant interactions involving two domains are reported. The binomial accuracy analyses were run using generalized linear models (glmer). The log-transformed response times were analyzed using linear models (lmer). All generalized linear models included the bobyqa optimizer to improve the model fit.

3 Results

3.1 Correlations

Correlations between language experience measures and the dependent variables of accuracy and response time (averaged across items, by-subject) are presented in Table 3.

Table 3. Correlations among language experience variables.

Variables	RT	L1 speaking	L1 understanding	L1 reading	L1 exposure	L2 speaking	L2 understanding	L2 reading	L2 exposure	L2 age of acquisition
Accuracy	-0.510*	-0.231	-0.143	-0.232	-0.242	0.660**	0.667*	0.624*	0.259	-0.785***
Response time		0.109	0.101	0.144	0.086	-0.145	-0.271	0.237	-0.052	0.377
L1 speaking			0.936***	0.940***	0.482*	-0.450	-0.421	-0.445	0.520*	0.376
L1 understanding				0.927***	0.442†	-0.409	0.363	-0.394	-0.472*	0.280
L1 reading					0.505*	-0.429	-0.385	-0.327	0.542*	0.327
L1 exposure						-0.438†	-0.279	-0.531*	-0.927***	0.309
L2 speaking							0.941***	0.803***	0.371	0.644**
L2 understanding								0.772***	0.187	0.652**
L2 exposure									0.476*	0.790***
L2 AOA										-0.312

***p < .001, **p < .01, *p < .05, and †p < .07

A moderate negative correlation was found between accuracy and response time (i.e. faster translations were more accurate), suggesting that there was no speed-accuracy trade-off. All L2 measures other than L2 current exposure showed significant positive correlations with translation accuracy (rs > 0.62, ps <. 01), while none of the L1 measures were correlated with accuracy (rs < 0.24). No measure was correlated with translation speed. For the cognitive ability measures, higher non-verbal IQ scores were correlated with lower translation accuracy ($r = -0.65$, $p < .05$) and longer translation time ($r = 0.56$, $p < .05$; see Table 4).

Table 4. Correlations among cognitive ability variables.

Variables	Working memory	IQ score	Inhibitory control
Accuracy	0.522†	-.645*	-0.373
Response time	-0.197	0.557*	0.228
Working memory		-0.459	0.180
IQ score			0.136

*p < .05, **p < .01, ***p < .001, and †p < .07

The correlations among word property measures and the dependent variables (averaged across subjects, by-item) are shown in Table 5. Similar to the by-subject results, a moderate negative correlation was found between accuracy and response time, suggesting that words with quicker responses were also more accurately translated. Phonological length and word frequency were correlated with translation performance. Specifically, greater phonological length was associated with lower accuracy ($r = -0.27$, $p < .01$) and longer response times ($r = 0.21$, $p < .05$), while more frequent words were associated with greater accuracy ($r = 0.27$, $p < .01$) and shorter response times ($r = -0.30$, $p < .01$). Bi-phone probability was positively correlated with translation time (r

= 0.27, $p < .01$), indicating that words with higher bi-phone probability were translated slower than words with lower bi-phone probability.

Table 5. Correlations among linguistic property variables.

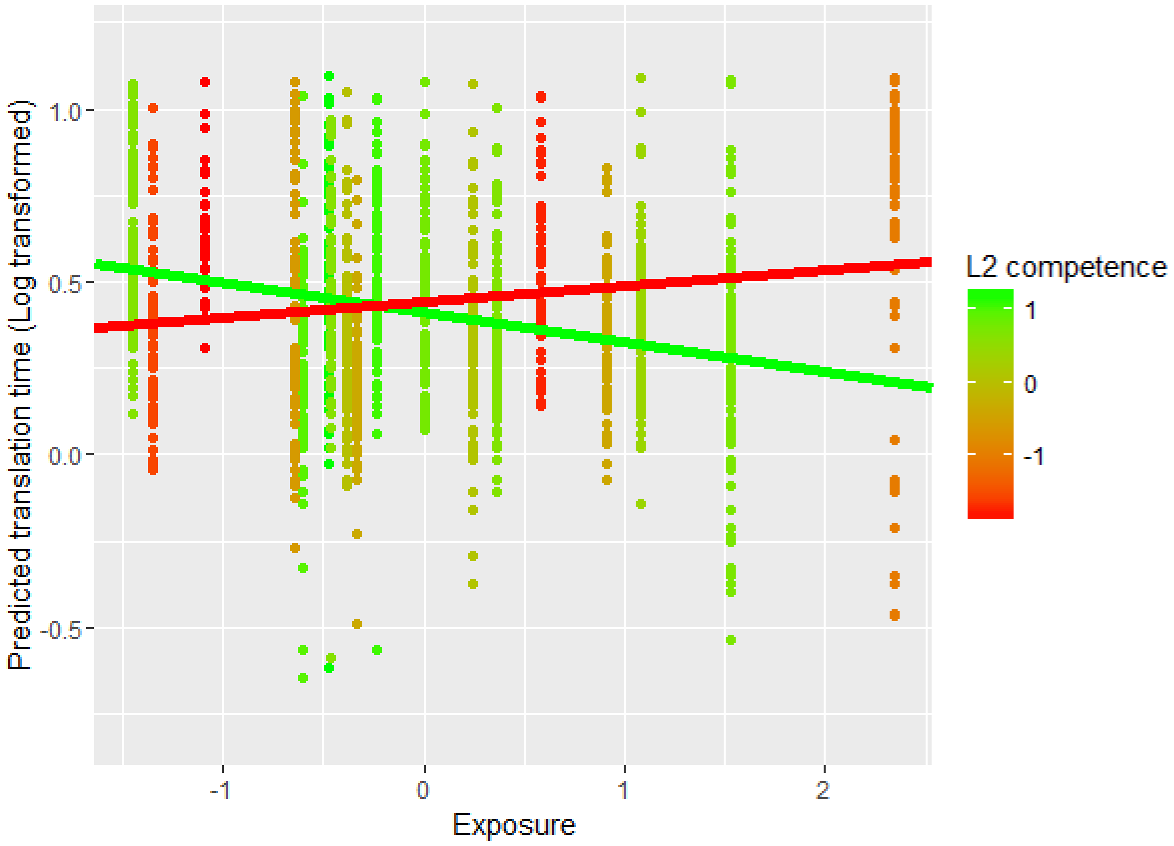
Variables	RT	Length O	Length P	Frequency	O Size	P Size	Bigram	Bi-phone
Accuracy	-0.41***	-0.148	-0.269**	0.266**	-0.075	-0.070	-0.169†	-0.166
Response time		0.150	0.206*	-0.303**	-0.068	0.096	0.117	0.269**
Orthographic length			0.648***	-0.226*	-0.662***	-0.472***	0.073	0.155
Phonological length				-0.262**	-0.423***	-0.523***	0.114	0.588***
Frequency					0.292**	0.256**	-0.005	-0.125
Orthographic size						0.654***	0.318***	0.005
Phonological size							0.208*	-0.050
Bigram probability								0.342***

*$p < .05$, **$p < .01$, ***$p < .001$, and †$p < .07$

3.2 Mixed Effects Modeling

Language Experience. For accuracy, L2 competence was the sole significant predictor ($\beta = 0.63$, $SE = 0.17$, $z = 3.65$, $p < 0.001$), such that participants with greater L2 competence were more accurate in their translations. For translation speed, there was a marginal interaction between L2 competence and exposure ($\beta = -0.07$, $SE = 0.04$, $t = -1.86$, $p = 0.08$). The exposure measure indexes the relative amount of L1-to-L2 exposure, such that higher values indicate relatively greater L1 exposure while negative values indicate relatively greater L2 exposure. Plotting this interaction shows that the effect of exposure may have opposite influences on translation time for bilinguals with higher and lower L2 competence (see Figure 1). Greater L1 exposure (relative to L2) tended to facilitate translations for bilinguals with higher L2 competence, while it tended to slow down translations for bilinguals with lower L2 competence.

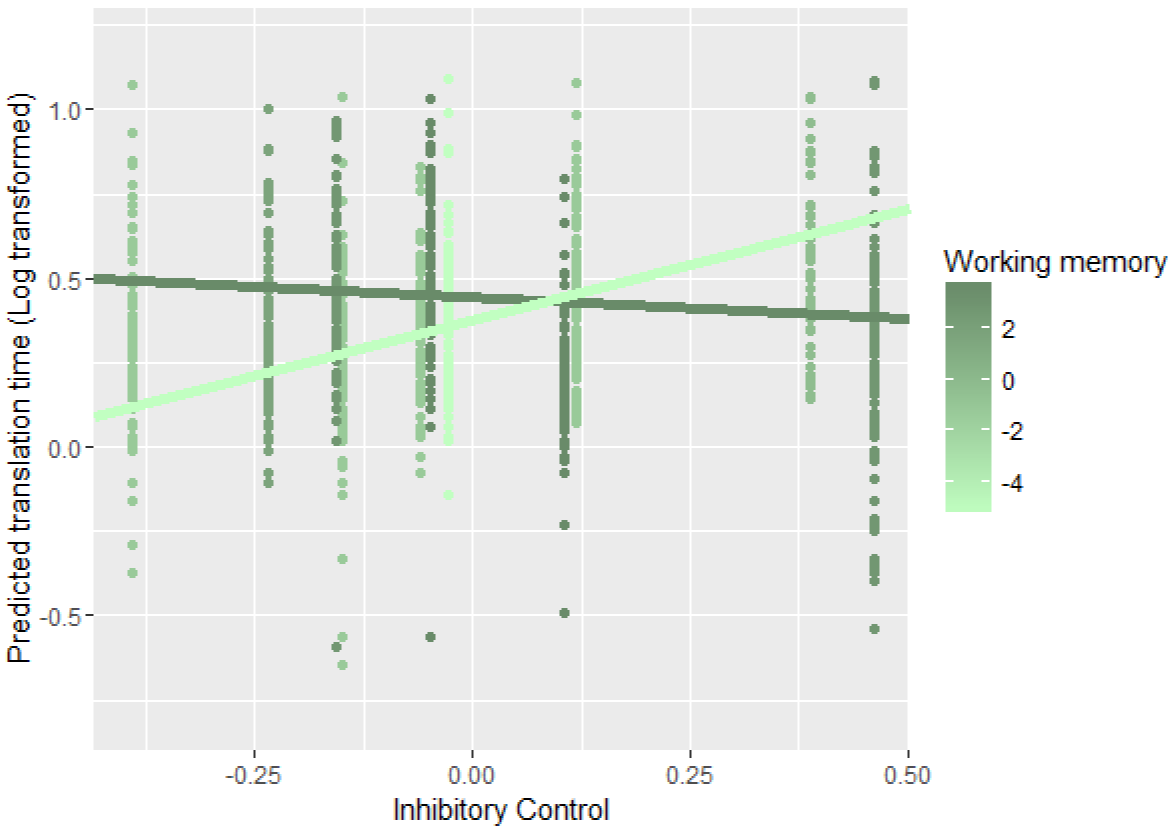
Figure 1.



Influence of L2 competence and Exposure on translation time. The color gradient represents low L2 competence (red) to high L2 competence (green). A more positive Exposure score indicates more exposure in L1 (and less exposure in L2). Low L2 competence (red line) and high L2 competence (green line) have different effects on translation time as the exposure score increases.

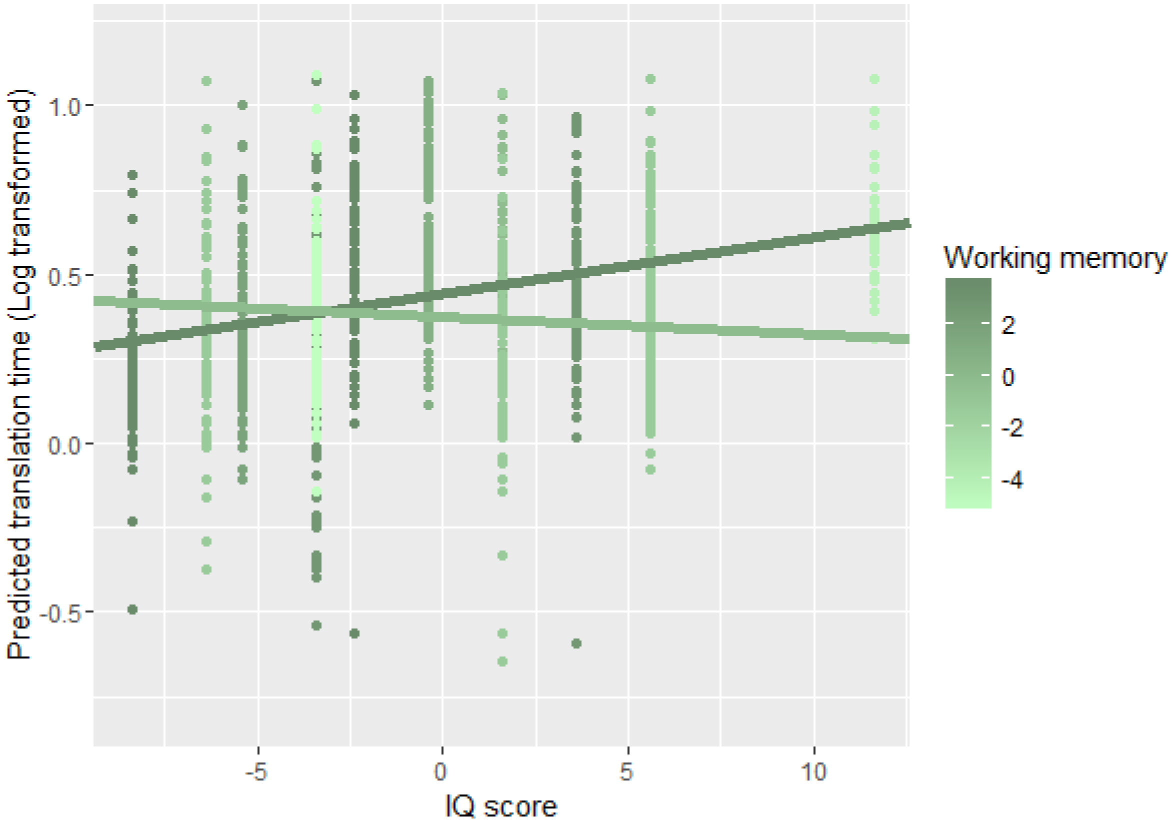
Cognitive Abilities. The main effect of inhibitory control on accuracy was significant (β = -2.08, *SE* = 0.87, *z* = -2.39, *p* = 0.02), indicating that better inhibitory control (i.e., smaller differences between neutral and incongruent conditions) was associated with greater accuracy. The main effect of inhibitory control on response time was also significant (β = 0.32, *SE* = 0.07, *t* = 4.57, $p < 0.001$), with better inhibitory control leading to faster translations. Additionally, there were significant interactions between working memory and inhibitory control (β = -0.15, *SE* = 0.05, *t* = -2.92, *p* = 0.01), IQ and inhibitory control (β = 0.04, *SE* = 0.02, *t* = 2.35, *p* = 0.04), and IQ and working memory (β = 0.004, *SE* = 0.001, *t* = 2.92, *p* = 0.01) for reaction time. Plotting the interaction between inhibitory control and working memory reveals that worse inhibitory control (more positive scores) increased translation time for bilinguals with low working memory but had less impact on bilinguals with high working memory (Figure 2). Meanwhile, the interaction between working memory and IQ shows that higher IQ increased the translation time for bilinguals with higher working memory, but decreased translation time for bilinguals with lower working memory (Figure 3). Finally, the interaction between IQ and inhibitory control reveals that increased IQ is related to increased translation time when inhibitory control is low (a higher difference score), but not high (a lower difference score; see Figure 4).

Figure 2.



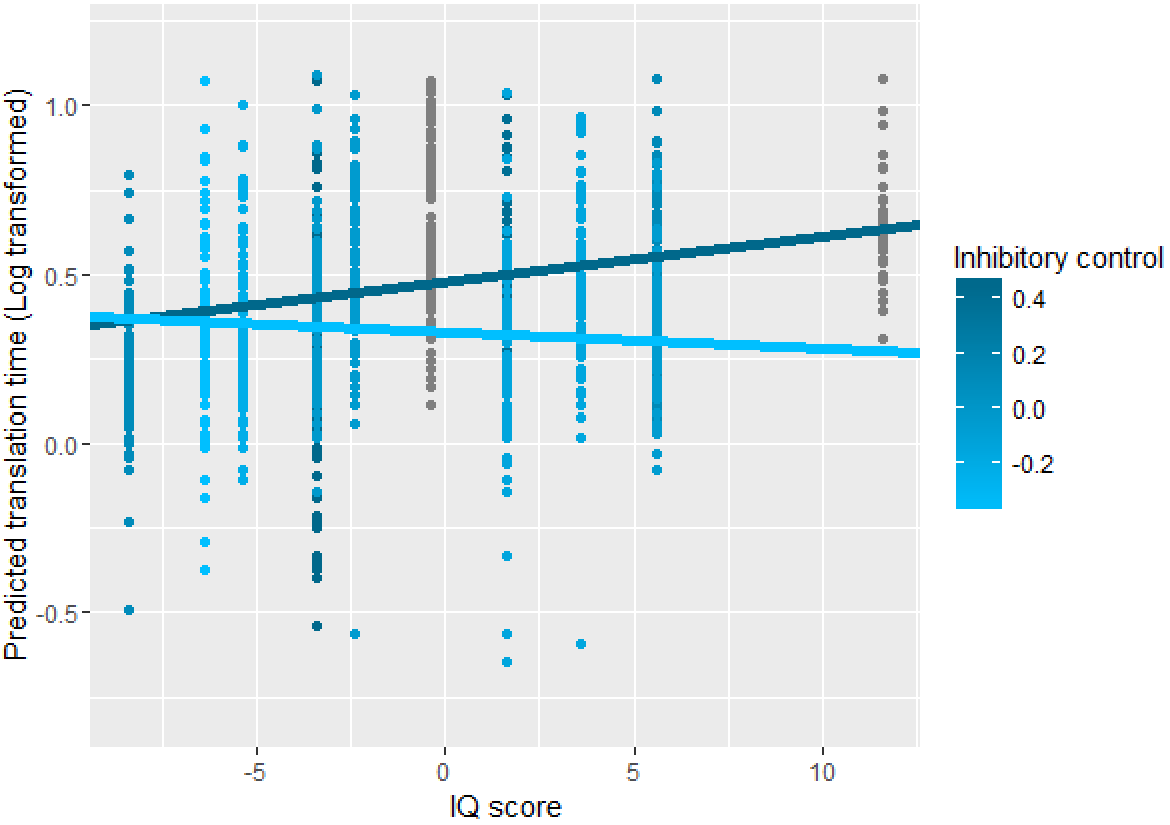
Influence of working memory and inhibitory control on translation time. The color gradient represents low working memory (light green) to high working memory (dark green). A more positive inhibitory control score indicates worse inhibitory control function (i.e., larger difference between neutral and incongruent conditions). This interaction shows that the influence of inhibitory control on translation time differs across high working memory (dark green) and low working memory (light green), with better inhibitory control reducing translation speed specifically for those with low working memory.

Figure 3.



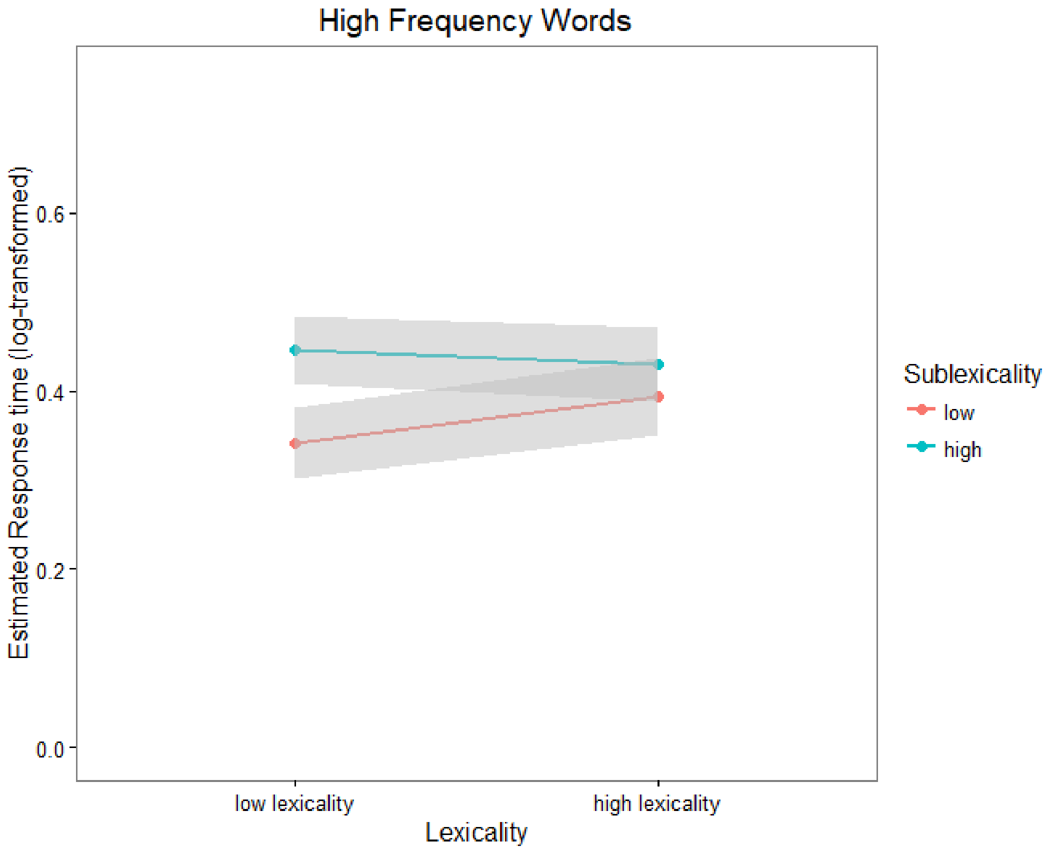
Influence of working memory and IQ on translation time. The color gradient represents low working memory (light green) to high working memory (dark green). This interaction shows that the influence of IQ on translation time differs across high working memory (dark green) and low working memory (light green), with higher IQ scores leading to longer reaction times, specifically for those with higher working memory.

Figure 4.



Influence of inhibitory control and IQ on translation time. The color gradient represents low inhibitory control (higher scores, dark blue) to high inhibitory control (lower scores, light blue). This interaction shows that the influence of IQ on translation time differs across high inhibitory control (light blue) and low inhibitory control (dark blue), with higher IQ scores leading to longer reaction times, specifically for those with lower inhibitory control.

Figure 5.



Influence of lexicality and sublexicality on translation time for high-frequency words. Words with less common sublexical features have shorter translation times than words with more common sublexical features. The effect of sublexicality on translation time is larger for words with lower lexicality than words with higher lexicality.

Word Properties. For the accuracy model, the main effect of frequency was significant (β = 0.384, *SE* = 0.10, z = 3.95, $p < 0.001$), such that more frequent words were translated more accurately. The main effect of frequency was also significant for reaction time (β = -0.0719, *SE* = 0.02, t = -4.42, $p < 0.001$), suggesting that words of higher frequency were translated faster. The three-way interaction between frequency, lexicality, and sublexicality on reaction time was also significant (β = -0.03, *SE* = 0.02, t = -2.07, p = 0.04). In order to understand this three-way interaction, words were divided into high and low frequency categories based on mean frequency. For words with high frequency, the interaction between lexicality and sublexicality was significant (β = -0.03, *SE* = 0.02, t = -2.03, p = 0.047) and the main effect of sublexicality was also significant, such that greater bi-phone and bi-gram probability led to longer reaction times (β = 0.05, *SE* = 0.02, t = 3.02, $p < 0.01$). The plot (Figure 5) shows that for high frequency words, the influence of the sublexical factor on response time increased in words with lower scores on the lexical factor (phonological and orthographic neighborhood density and orthographic length). In contrast, none of the main effects or interactions were significant for words with low frequency (*p*s > 0.43).

Interaction between language experience and cognitive ability. The best-fitting model for accuracy included L2 competence, IQ, inhibitory control, as well as all interaction terms among them. There was a significant interaction between L2 competence and inhibitory control (β = 1.72, *SE* = 0.77, z = 2.23, p = 0.03). Follow-up analysis showed that greater inhibitory control was particularly helpful for bilinguals with lower L2 competence (β = -3.13, *SE* = 0.79, z = -3.97, $p < 0.001$). No other interactions approached significance (all $p > .05$). The best-fitting response time model included L2 competence, working memory, and inhibitory control, as well as their interaction terms. There was a marginally significant three-way interaction (β = -0.28, *SE* = 0.13, *t* = -2.13, *p* = 0.057), and follow-up analyses revealed that the previously observed interaction between inhibitory control and working memory was restricted to bilinguals with higher L2 competence (β = -0.30, *SE* = 0.05, *t* = -6.48, *p* < 0.001). In other words, high levels of inhibitory control may offer protection against the negative effects of low working memory, but only for bilinguals who also have higher levels of L2 competence.

Interaction between language experience and word properties. The best-fitting accuracy model included L2 competence, word frequency and their interaction term. However, the interaction between these two variables was not significant (*z* < 1.5, *p* > 0.1). The best-fitting response time model included exposure to L2, sublexicality, and word frequency, as well as their interaction terms. The three-way interaction among these factors was significant (β = 0.02, *SE* = 0.01, *t* = 2.15, *p* = 0.03). Separate analyses of bilinguals with high vs. low L2 exposure revealed that the facilitative effect of higher L2 word frequency was significant for bilinguals with higher L2 exposure (β = -0.08, *SE* = 0.02, *t* = -4.15, *p* < 0.001), but only marginal for those with lower L2 exposure (β = -0.04, *SE* = 0.02, *t* = -2.01, *p* = 0.050). In other words, bilinguals with lower L2 exposure were less sensitive to L2 word frequency.

4 Discussion

The present study provides a broad investigation of translation ability by examining variables from two different domains: cognitive abilities, and linguistic factors, including language experience of the translators and the characteristics of the language to be translated. The results not only replicated previously documented effects, but also revealed several novel interactions across measures and domains. Before discussing each domain in further detail, we summarize the key findings as follows:

- **Translation performance varies as a function of language background, cognitive abilities, and word properties.** More accurate and/or faster translations were associated with greater L2 competence, better inhibitory control, and higher word frequency.
- **Advantages in one domain/function may compensate for disadvantages in others.** Greater inhibitory control led to faster reaction times for those with lower working memory, as well as for those with lower L2 competence. Individuals with lower L2 competence additionally benefited from more L2 exposure.
- **Word properties influence translations in a hierarchical fashion.** Word frequency had a global effect on translation performance, with sublexical effects (i.e., the commonality of sound/letter combinations within a word) emerging for high frequency words, and lexical effects (i.e., frequency of words with similar sounds/forms within a language) emerging for words with high frequency and low sublexicality.

4.1 Language Experience

L2 competence, a composite score of self-rated proficiency on reading, understanding, and speaking L2, as well as L2 age of acquisition, turned out to be the main factor in determining accuracy of translation from L2 to L1. Specifically, bilinguals with higher L2 competence were more accurate in translating L2 words to L1, most likely due to better and faster recognition of words in the source language (L2). This finding is consistent with past work demonstrating that higher L2 proficiency is associated with more accurate translations (e.g., Kroll et al., 2002; Prior et al., 2013). Age of acquisition is often a reliable predictor of one’s second language ability

(Birdsong, 2006), and has been found to predict performance in other L2 tasks such as faster picture naming (Litcofsky, Tanner, & van Hell, 2016), lexical access (Canseco-Gonzalez et al., 2010), and more native-like sentence comprehension (McDonald, 2000). As expected, our results show that L2 proficiency and age of acquisition are important predictors of (backward) translation ability.

We expected to see some effect of L1 competence or exposure to L1 on translation performance because the nature of the translation task requires proficiency in both the source language (L2) and the target language (L1). We did not find support for this hypothesis, as none of the L1 measures in either the mixed effects models or the correlation analysis showed effects on translation accuracy or speed. This may be because all participants in the present study had high L1 proficiency, with relatively little variance. As a result, we may observe a greater role of L1 competence among bilinguals with more variable levels of native proficiency (e.g., heritage speakers). We did, however, find a marginally significant interaction between L2 competence and relative exposure to L1 versus L2. For those with higher L2 competence, faster translation times were associated with relatively greater L1 exposure (or less L2 exposure). This may be because increased L2 competence can reduce verbal fluency in L1 (Linck et al., 2009), and so a certain amount of exposure to the target language (L1) may ensure successful lexical access and retrieval. For those with lower L2 competence, on the other hand, faster translations were associated with relatively greater L2 exposure, suggesting that greater exposure may compensate for lower reading, speaking, and comprehension skills. Future comparisons of backward and forward translation tasks may additionally shed light on whether greater L2 exposure has differential benefits depending on whether the task requires L2 comprehension or production.

4.2 Cognitive Abilities

Among the cognitive ability measures, inhibitory control emerged as the primary factor influencing translation performance. Specifically, bilinguals with better inhibitory control were both more accurate and faster at translating. This finding is consistent with previous work on translation ability (Michael et al., 2011), as well as with research showing that inhibitory control affects both bilingual language comprehension (Blumenfeld & Marian, 2011; Macizo, Bajo, & Martín, 2010) and production (Abutalebi & Green, 2007; Kroll et al., 2008). Greater inhibitory control may aid in translation through more efficient coordination of the two language systems, as translators are required to quickly shift between the target and the source language, and select the appropriate word for production (de Groot & Christoffels, 2006). Inhibitory control may therefore influence how quickly and accurately bilinguals can switch between comprehending one language and producing the other. Alternatively, inhibitory control may exert a more indirect effect on translation ability by facilitating vocabulary learning (Michael et al., 2011). Indeed, we found that the effect of inhibitory control was moderated by L2 competence, such that the benefits of better inhibitory control were most pronounced for those with lower L2 competence. This may suggest that domain-general cognitive skills can be recruited to compensate for lower language competence, either directly, by facilitating the coordination of multiple languages, or indirectly, by bolstering vocabulary acquisition.

While either mechanism could plausibly explain the relationship between inhibitory control and L2 competence, the similar interaction observed between inhibitory control and working memory may provide support for the “direct” coordination function. Specifically, better inhibitory control led to faster translation times for those with lower, but not higher working memory, indicative of compensatory functions within the cognitive ability domain. Unlike inhibitory control, however, there was no main effect of working memory. Instead, we observed that higher working memory led to faster translations only among those with higher IQ. Past work has revealed mixed findings regarding the impact of working memory on translation, with some studies finding an overall benefit (Christoffels et al., 2006; Kroll et al., 2002), and others showing no effect (Michael et al., 2011). Our findings suggest that such differences may result, in part, from interactions between working memory and other cognitive abilities such as inhibitory control and IQ.

Effects of intelligence in the present study, however, should be interpreted with caution as there is reason to believe that intelligence may have been confounded with language experience. In the initial correlation analysis, we observed that higher IQ was unexpectedly negatively associated with translation ability (i.e., lower accuracy and longer translation time). Careful examination of individual data revealed that participants with higher IQ scores were mostly doctoral students who came to the U.S. to attend graduate school in their early twenties. Considering that L2 age of acquisition was also correlated with translation performance, this may explain why bilinguals with higher IQ scores tended to be worse at translating. To test this hypothesis, we conducted a separate mixed effects analysis with L2 age of acquisition, IQ score, and their interaction term as fixed effects, with random intercepts for subject and item. The only significant effect was L2 age of acquisition ($\beta = -0.18$, $SE = 0.05$, $t = -3.73$, $p < 0.001$), suggesting that the surprising negative effect of IQ score was most likely an artifact of the participant population.

Regardless of the effects of IQ, however, the interactions among inhibitory control, working memory, and L2 competence, as well as between L2 competence and language exposure suggest that the process of translation relies on multiple domains of cognitive and linguistic ability that may supplement or compensate for one another. For instance, when a bilingual has superior working memory, his or her disadvantage in inhibitory control may have a reduced effect on translation performance. On the other hand, for someone with low working memory, increased inhibitory control may help boost performance. Furthermore, analyses across domains revealed that the interaction between inhibitory control and working memory was restricted to bilinguals with higher L2 competence, suggesting that distinct cognitive abilities may only compensate for each other after a certain level of language competence is established. The current study is among the first to simultaneously investigate different cognitive functions and components of language experience, revealing the dynamic and interactive influence of domain-general and domain-specific skills on translation performance.

4.3 Word Properties

As expected, word frequency had a significant impact on translation accuracy and speed, as revealed by both linear models and correlations. This finding replicates previous studies showing that higher word frequency was associated with shorter response times and higher accuracy during translation (e.g., de Groot et al., 1994). Additionally, frequency modulated the interaction between lexical and sublexical features on translation time. For high-frequency words, translation time was affected by sublexical information (e.g., the commonality of the specific phoneme combinations in a word), even when accounting for lexical features such as phonological neighborhood density. Specifically, words with more common phoneme combinations took longer to translate. This effect is consistent with Vitevitch and Luce’s (1999) observation that higher bi-phone and bi-gram probabilities (i.e. sublexical features) were associated with slower recognition times.

Furthermore, the influence of sublexical features on high-frequency-word translation time was greater for words scoring low on the lexical factor (e.g., those that have fewer similar sounding words) than words scoring high on the lexical factor (e.g., those with more similar sounding words). This result suggests that bilinguals are sensitive to features at the phoneme level so long as the word does not have many similar sounding neighbors at the lexical level. This finding is consistent with the phenomenon in spoken word recognition where competition at the lexical level can obscure and override sublexical effects (Vitevitch & Luce, 1999; Vitevitch, Luce, Pisoni, & Auer, 1999). On the other hand, low-frequency-word translation time was not affected by either lexical or sublexical information. These findings together reveal the importance of word frequency, not only through its direct influence on translation performance, but also as a moderator for more fine-grained effects of lexical and sublexical frequency information.

5 Conclusion

The current study examined the independent and interactive effects of language experience, cognitive abilities, and word properties on translation ability. Among the variables, greater second language competence, better inhibitory control, and higher word frequency emerged as the primary predictors of successful performance, both in terms of faster response times and higher accuracy. Furthermore, these variables modulated the effects of language exposure, working memory, as well as lexical and sublexical properties on translation performance. The presence of interactions both within and across domains strongly suggests that participant- and stimulus-related attributes can alter the nature of the relationship among different predictors. An important step moving forward, then, will be to determine whether similar relationships are observed with more complex, naturalistic forms of translation, as well as across bilinguals with varying degrees of translation experience. In sum, our findings suggest that the ubiquitous and often effortless practice of translation is in fact supported by factors related to the language itself, as well as by individual differences in both linguistic and cognitive abilities. Critically, we demonstrate that the multifaceted and dynamic relationship between the language and the bilingual impacts even the simplest forms of de-contextualized translation.

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Conflict of Interests

The authors declare no conflicts of interest.

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Appendix A. English stimuli and their Chinese translations.

English	Chinese	English	Chinese	English	Chinese	English	Chinese
year	年	ear	耳	make	做	burn	烧
day	天	egg	蛋	think	想	sing	唱
word	词，字	leaf	叶	take	拿，取	guess	猜
friend	友	bag	包	give	给	shut	关，闭
door	门	shoe	鞋	use	用	hurt	伤，害
car	车	lip	唇	ask	问	sweep	扫
home	家	cup	杯	put	放	mix	混，拌
foot	脚	boat	船	try	试	freeze	冻，冰
street	街	brain	脑	live	活	rub	擦，揉
bed	床	breast	胸	bring	带	dig	挖
wall	墙	neck	脖	sit	坐	wipe	擦
tree	树	card	卡	let	让	suck	吸，吮
floor	地	hat	帽	speak	说，讲	grab	抓，抢
leg	腿	cat	猫	learn	学	hate	恨，厌
mouth	嘴	path	路	eat	吃	beg	求
blood	血	snow	雪	send	送	squeeze	挤，压
oil	油	side	侧，边	draw	画	grind	研，碾
shop	店	sand	沙	build	建	lend	借
hill	山	cloud	云	stay	留	spin	转，旋
stone	石	ice	冰	love	爱	bake	烤，烘
dog	狗	flesh	肉	kill	杀	melt	熔，化
bird	鸟	lake	湖	cut	切，砍	crawl	爬
gun	枪	song	歌	choose	选，择	fry	煎，炸
king	王	cloth	布	laugh	笑	starve	饿
milk	奶	chain	链	throw	扔，投	toss	抛
meal	餐，饭	drug	药	win	赢	soak	浸，泡
edge	边	coal	煤，碳	teach	教	bind	捆，绑
grass	草	knife	刀	hang	挂，悬	thank	谢
desk	桌	ash	灰	seek	寻，找	wash	洗
gold	金	say	说	tooth	牙	go	去，走