

Individual differences in L2 frequency effects in different script bilinguals

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Abstract

Aims: High frequency words are read more quickly and accurately than low frequency words, a phenomenon called the frequency effect. In the current study, we examine several possible predictors for explaining individual differences between bilinguals in their sensitivity to frequency in the second language: specific second language exposure and vocabulary; general language abilities (therefore also evident in native language performance); and general cognitive ability (non-linguistic sensitivity to regularities).

Approach: We used an individual differences approach with unbalanced Hebrew–English bilinguals, two typologically different languages that do not share a writing system, which allows a clear discrimination between native language and second language exposure and vocabulary.

Data and analysis: To examine frequency effects, 69 Hebrew–English bilingual adults completed lexical decision tasks in native language and second language. In addition, participants completed vocabulary tests in both languages, reported language use and proficiency, and performed a statistical learning task. Data were analyzed using linear mixed-effects models.

Findings: The results demonstrated that only vocabulary knowledge in the second language was a significant predictor of frequency effects in the second language. In addition, neither sensitivity to frequency in the native language nor statistical learning ability (a measure of general sensitivity to regularities) predicted sensitivity to frequency in the second language.

Originality: Using an individual differences approach with bilinguals of two typologically different languages that do not share a writing system allows us to distinguish between native language and second language proficiency, and therefore identify the unique contribution of predictive factors from each of the languages to efficient visual word recognition in second language.

Implications: The current findings support the lexical entrenchment hypothesis and highlight the importance of testing a variety of bilingual populations.

Keywords

Frequency effect, visual word recognition, L2, reading, bilingualism, second language, vocabulary, visual statistical learning

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Introduction

Individuals differ in their language learning and processing abilities, differences that are especially prominent in non-native languages (Dörnyei, 2014; Koda, 2005). Such variability in second language (L2) processing efficiency might be a result of individual differences in specific L2 knowledge and exposure, and/or in general linguistic processing abilities (therefore evident in both native language (L1) and L2 performance). Finally, it is also possible that variability in L2 processing results from differences in domain general cognitive mechanisms. In the current study, we investigate L2 visual word recognition efficiency in different script bilinguals, from an individual differences' perspective (Kidd, Donnelly, & Christiansen, 2018), to address these important questions.

Proficient adult readers are extremely efficient in visual word recognition and can extract meaning from print in less than half a second (for a review, see Carreiras, Armstrong, Perea, & Frost, 2014; Kuperman, Drieghe, Keuleers, & Brysbaert, 2013). According to the lexical quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002), efficient reading requires that readers have a high quality mental representation of the word, namely – accessible knowledge about the form (phonological, morphological, syntactic, and orthographic knowledge) and meaning (semantic knowledge) of a word. High quality lexical representations lead to rapid and effortless word recognition.

One factor that is linked to high quality lexical representations is word frequency. That is, words that appear more often in written language become more accessible over time. Indeed, in studies of visual word recognition, high frequency words are recognized more quickly than low frequency words (e.g. Rayner & Duffy, 1986; Scarborough, Cortese, & Scarborough, 1977). This is termed the frequency effect and reflects sensitivity of readers to the distributional properties of written language at the whole-word level. Frequency effects are an experimentally well-established finding in both behavioral and eye-movement measures, and have been demonstrated across alphabetic and non-alphabetic languages (e.g. Cop, Keuleers, Drieghe, & Duyck, 2015; Gollan, Slattery, Goldenberg, Van Assche, Duyck, & Rayner, 2011; Li, Bicknell, Liu, Wei, & Rayner, 2014; Liu, Li & Han, 2015; Liu, Reichle, & Li, 2016; Pivneva, Mercier, & Titone, 2014; Rau, Moll, Snowling, & Landerl, 2015; Whitford & Titone, 2012) including Hebrew (Frost, 1994; Koriat, 1984). Further, frequency effects have been demonstrated in both the L1 and the L2 of bilingual readers (Cop et al., 2015; Duyck, Vanderelst, Desmet, & Hartsuiker, 2008; Whitford & Titone, 2012).

However, most previous studies have demonstrated frequency effects at the group level, and only a handful of studies have examined them from an individual differences' perspective (Brysbaert, Lagrou, & Stevens, 2017; Diependaele, Lemhöfer, & Brysbaert, 2013), as done in the current study. Further, only two studies to date have examined frequency effects in both the L1 and L2 of the same readers, and have included measures of participants' proficiency in both languages (Cop et al., 2015; Whitford & Titone, 2012), and these two studies report conflicting results regarding the contribution of L1 abilities to L2 processing (elaborated below). It is important to study individual differences in frequency effects in both languages of bilinguals because such investigations can inform our understanding of the degree to which mechanisms supporting high-quality lexical representation might be shared across their two languages. Thus, the first goal of the current study is to add to this literature and further examine possible contributions of L2 and L1 proficiency and exposure to variability in L2 frequency effects.

In addition, the current study goes beyond previous research in three important ways. First, whereas previous individual differences studies have examined bilingual speakers of typologically similar languages (Dutch–English, French–English, and German–English) the current study examined bilingual speakers of Hebrew and English, two languages that are typologically different and do not share an orthography. This is important, because the degree to which L1 abilities might contribute to L2 processing can differ depending on language similarity. Second, we investigate a

novel aspect of L1 abilities, namely the sensitivity to frequency in the L1, as a possible predictor of sensitivity to frequency in L2. This variable will allow us to ask whether the ability to build high quality lexical representations might be a characteristic of an individual, which can then be expressed in the various languages she uses. Finally, we also investigated the possible contribution of non-linguistic sensitivity to regularities, in a visual statistical learning (VSL) task, to variability in frequency effects in L2 word recognition. Thus, we broaden our scope even further to ask whether the cognitive system's ability to represent distributional properties of the environment is shared across linguistic and non-linguistic domains.

L2 exposure and vocabulary as predictors of L2 frequency effects

Readers are more often exposed to words that occur frequently in the language than to less frequent words. There is a positive relation between written word exposure and reading efficiency, which is especially prominent among unskilled readers. Thus, exposure to print makes a strong contribution to word reading efficiency in children at early stages of reading acquisition (e.g. Cunningham & Stanovich, 1997; Strasser, Vergara, & del Río, 2017). However, the function of exposure, or frequency, is logarithmic, reflecting the finding that at some point additional exposure does not further improve performance, namely there is a ceiling-effect (e.g. Monsell, 1991; Morton, 1970). Consequently, as overall exposure to written language increases in skilled readers, differences in word recognition times between low and high frequency words become less pronounced. This is because efficiency for processing high frequency words stops improving, whereas additional exposure to low frequency words leads to continuing improvements in efficiency. Hence, the positive relation between word frequency and reading efficiency might be modulated by the amount of exposure (Brysbaert et al., 2017; Diependaele et al., 2013; for a recent computational model see Monaghan, Chang, Welbourne, & Brysbaert, 2017).

The logarithmic nature of the relation between language exposure and frequency effects is also suggested by the frequency lag hypothesis (Gollan et al., 2011; also referred to as the weaker links hypothesis, Gollan, Montoya, Cera, & Sandoval, 2008) and the lexical entrenchment hypothesis (Brysbaert et al., 2017; Diependaele et al., 2013). These theoretical approaches claim that larger frequency effects for bilinguals are a result of the fact that they use each language only part of the time, and therefore have less exposure to word forms in each language, compared to monolinguals. Gollan et al. (2011) partly confirmed this prediction in a study comparing frequency effects in English between English speaking monolinguals and two groups of bilinguals who learned English as their L2 (Spanish–English and Dutch–English speakers), using a lexical decision task. As predicted by the frequency-lag hypothesis, the Dutch–English bilinguals exhibited larger frequency effects than the monolinguals. However, there was no difference in the magnitude of the frequency effect between the Spanish–English bilinguals and the monolinguals, a finding that might be explained by the higher level of English exposure that was reported by the Spanish–English bilinguals compared to Dutch–English bilinguals.

Larger frequency effects in English for Dutch–English bilinguals compared to English speaking monolinguals were also reported by Duyck et al. (2008) and Cop et al. (2015), who investigated unbalanced bilinguals who had relatively lower exposure to English (see also Diependaele et al., 2013). Further reinforcing this claim, Whitford and Titone (2012) also found larger frequency effects in the L2 than in the L1 in two groups of unbalanced bilinguals (English–French and French–English). This last study also reported that lower L2 exposure levels led to larger L2 frequency effects, reinforcing the importance of examining this issue from an individual differences' perspective.

Although research has identified exposure as important for understanding frequency effects in the L2, in practice exposure is difficult to measure accurately, and often relies on self-reports. Further, although greater exposure undeniably leads to vocabulary growth (e.g. Paradis & Jia, 2017; Stanovich & Cunningham, 1992), individual differences in language learning abilities might lead different learners to benefit to various degrees from the same amount of language exposure (e.g. Robinson, 2003; Van Patten, 2015), and thus reach variable levels of proficiency. Therefore, several studies have investigated to what degree language proficiency, and specifically the vocabulary knowledge of the reader might predict frequency effects. Thus, Diependaele et al. (2013) reported a negative relation between vocabulary size and frequency effects in monolingual and bilingual readers in English (see also Butler & Hains, 1979; Lemhöfer, Dijkstra, Schriefers, Baayen, Grainger, & Zwitserlood, 2008; Yap, Balota, Sibley, & Ratcliff, 2012). One explanation for this finding is that the probability of low frequency words having high quality lexical representations increases as vocabulary size increases (e.g. Baayen, 2001).

In the current study we included both self-rated exposure and objective vocabulary measures in the L2 to examine which of these might better capture variance that is most relevant for understanding differences in frequency effects.

L1 vocabulary and frequency effects as predictors of L2 frequency effects

There is considerable variation in the vocabulary knowledge of adults in their native language, which has recently been linked to education level as well as print exposure and language aptitude (Dąbrowska, 2018). In a recent study, Cop et al. (2015) suggested that individual differences in L1 vocabulary knowledge of young adult university students reflect mostly a general language aptitude because most university students arguably have similar educational backgrounds and are of similar age (though background is of course not identical even within this population). They put forth this suggestion to explain their somewhat surprising finding that L1 vocabulary knowledge (but not L2 vocabulary knowledge) was found to predict frequency effects in eye-movement measures of word reading in both languages of Dutch–English bilinguals.

However, an alternative, or additional interpretation is possible. Participants in the Cop et al. (2015) study were speakers of Dutch and English, bilinguals whose L2 was typologically similar to the L1, and used the same orthography (namely, the Roman alphabet). Under such circumstances, L2 exposure and vocabulary are less clearly distinct from those of L1, because when languages share the same alphabet, the reader has a shared exposure to the most basic characteristics of the written languages (Kempe & MacWhinney, 1996). Further, it has recently been demonstrated that bilinguals who read different script languages (Hebrew and English), found it easier to avoid cross-language intrusions and implement language control than readers of same-script languages (Spanish and English) (Fadlon, Li, Prior, & Gollan, 2019).

In addition, in typologically close languages there is inevitable overlap in some vocabulary items due to cognates and interlingual homographs (Diependaele et al., 2013; Lemhöfer et al., 2008). This overlap was demonstrated recently in a computational model by Monaghan et al. (2017), where Dutch was introduced to a “monolingual” English speaking model. Upon initial introduction, the model correctly pronounced 24% of Dutch words and semantically identified 6% of Dutch words – reinforcing the notion of significant cross-linguistic overlap (see also Schepens, Dijkstra, & Grootjen, 2012). Thus, it is possible that in bilingual speakers of similar languages there are strong associations between vocabulary knowledge in L1 and L2 (as indeed mentioned by Cop et al., 2015, though they do not report the actual correlation found), and specifically that they might be less well differentiated when entered in prediction models.

Thus, in the current study we set out to further investigate the possible contribution of L1 vocabulary knowledge, as an indicator of participants' general facility in creating high quality lexical representations, to L2 frequency effects. The participants in the current study were bilingual speakers of Hebrew and English, languages that differ both typologically and orthographically, allowing us to assume very little overlap between L1 and L2 oral and written vocabulary knowledge. Thus, the current design allows us to isolate the general language aptitude, as reflected in L1 vocabulary knowledge, from specific L2 knowledge.

In the current study, we go beyond previous investigations, by also probing the possible links between the magnitude of frequency effects in L1 and L2. Specifically, we suggest that individual differences in L1 frequency effects can be thought of as indicating the reader's facility in creating high quality lexical representations even for low frequency items. Thus, individuals who more easily construct such representations, following relatively few exposures to a given word, will have smaller frequency effects in the L1 than individuals who require a larger number of exposures to create a durable lexical representation for low frequency words. The question we wish to examine here is to what degree such efficiency might generalize across languages. In other words, would individuals with smaller frequency effects in L1 also tend to have smaller frequency effects in L2, after controlling for variability in other predictors such as vocabulary knowledge and specific language exposure?

General sensitivity to regularities

Finally, the current study examines one additional possible factor that might contribute to individual differences in L2 frequency effects, namely overall sensitivity to non-linguistic regularities. Statistical learning, or individuals' ability to extract regularities from the environment, has been postulated as a mechanism that might contribute to language learning and processing (for recent reviews see Arciuli, 2017; Erickson & Thiessen, 2015). Several studies report links between statistical (or implicit) learning abilities and different aspects of *native* language processing. Evans, Saffran, and Robe-Torres (2009) found that statistical segmentation abilities were related to receptive and expressive vocabulary size in school-aged children. Misyak and Christiansen (2012) report that statistical learning of non-adjacent dependencies predicts grammar processing (see also Kidd, 2012; Kidd & Arciuli, 2016). Arciuli and Simpson (2012) find that statistical learning of adjacent dependencies is related to reading ability in children and adults, a relation also found by Spencer, Kaschak, Jones, and Lonigan (2015). Finally, Conway, Bauernschmidt, Huang, and Pisoni (2010) report a significant link between implicit statistical learning and listeners' ability to predict upcoming words in discourse.

Much less is known about the possible contribution of statistical learning to *second* language learning and processing. Kaufman, DeYoung, Gray, Jiménez, Brown, and Mackintosh (2010) reported an association between implicit learning of regularities and academic performance in a foreign language (French or German) among native English-speaking adolescents. Frost, Siegelman, Narkiss, and Afek (2013) demonstrated that individual differences in statistical learning predicted young adults' acquisition of morphological regularities in Hebrew as an L2. Recently, Brooks, Kwoka, and Kempe (2017) similarly showed in a laboratory training study that individual differences in statistical learning predicted young adults' performance on learning a novel system of case markings (see also Onnis, Frank, Yun, & Lou-Magnuson, 2016).

The extant studies have mostly focused on the role of statistical learning in relatively early stages of L2 learning (Brooks et al., 2017; Frost et al., 2013). In the current study, we test this putative role in a population of intermediate-advanced L2 speakers. Further, we examine the possible role of statistical learning for an aspect of L2 processing that has not previously been examined,

namely frequency effects, which as described above, rely on participants' ability to create high quality lexical representations. Because the laboratory statistical learning task provides all participants with equal and well controlled exposure to a given input stream, it allows for easily comparing their ability to create high quality, distinguishable representations of repeating units within the stream, albeit not in the domain of language. We can then examine whether such abilities in the non-linguistic domain might be linked to frequency effects in reading L2 words.

The current study

In the current study, we examine the possible contribution of L2 variables, L1 variables, and statistical learning (a domain-general cognitive variable) in predicting efficient L2 visual word recognition, as reflected in the magnitude of word frequency effects in a lexical decision task.

The L2 variables included self-reported exposure levels and a vocabulary test. In line with previous research (behavioral: Cop et al., 2015; Diependaele et al., 2013; Duyck et al., 2008; Gollan et al., 2011; Whitford & Titone, 2012; computational: Monaghan et al., 2017), we hypothesize a negative relation between these measures and L2 frequency effects. L1 abilities are indexed by participants' L1 vocabulary knowledge and L1 frequency effects, in an L1 that is typologically different from the L2. A possible relation between L1 performance and the magnitude of the L2 frequency effects within the same reader, suggests a shared underlying mechanism. In contrast, a finding that these indices are not linked to frequency effects in the L2, might suggest that the formation of high-quality lexical representations is shared to a lesser degree in cases of dissimilarity between L1 and L2. General sensitivity to regularities is measured using a VSL task. A possible relation between VSL performance and L2 frequency effects will support the notion of a general cognitive mechanism which contributes to L2 reading efficiency. Finally, we expect to replicate the well-established finding of larger frequency effects in L2 than in L1, due to participants' lower exposure and proficiency levels in their L2 than in L1.

Method

Participants

Participants were 69 university students (48 females; mean age 25.03), recruited through advertisements offering payment or course credit for participating. All participants were unbalanced Hebrew–English bilinguals, with Hebrew as their native and dominant language (L1), and English as their second language (L2), learned as a foreign language in a school setting, from third grade. Participants were not proficient in any other language. All participants had normal or corrected to normal vision, without reported reading disability, attention disorders or language impairment. All participants provided written informed consent.

Materials

Language experience and proficiency questionnaire (LEAP-Q). A Hebrew translation (Prior & Beznos, 2009) of the (LEAP-Q (Marian, Blumenfeld & Kaushanskaya, 2007, Cronbach's alpha for L2 = 0.88, for L1 = 0.92) was used. The questionnaire includes questions regarding language exposure, use and proficiency, in the context of oral and written language, and yields scores for Hebrew and English proficiency and exposure on a 1–10 scale. Ratings of L2 exposure were used as predictors for the frequency effect in L2.

Table 1. Target word characteristics.

	Frequency per million words		Length in phonemes		Length in letters	
	Hebrew	English	Hebrew	English	Hebrew	English
Mean	49.91	49.65	4.7	4.38	3.92	5.22
Standard deviation	76.92	72.55	1.18	1.09	0.89	0.98
Maximum	409.8	420.61	8	9	6	9
Minimum	2	1.55	3	3	2	4

A reading fluency test was used as an objective measure of reading proficiency in the two languages, to supplement self-ratings of proficiency. An English version and a Hebrew version of the Test of Word Reading Efficiency (TOWRE; English version: Torgesen, Wagner, & Rashotte, 1999, average test–retest reliability > 0.9; Hebrew version: Katzir, Schiff, & Kim, 2012, Cronbach’s alpha = 0.95) were used to measure word reading efficiency in participants’ L1 and L2. In each version, the test contains 104 words, ordered in increasing level of difficulty, arranged in four columns. The participant is required to read aloud as many words as possible within 45 seconds. Separate scores were calculated for reading efficiency in Hebrew and English. The Hebrew version presented words without diacritics.

Vocabulary knowledge test (Shipley). Two versions of the vocabulary test, in Hebrew and English (English version: Shipley, 1946, split half internal consistency reported as 0.87 by Zachary, 1991; Hebrew version: Gilboa, unpublished) were administered. The test consists of 40 multiple-choice questions, presented in writing, in which participants are asked to choose which of four words is closest in meaning to a target word, with no time limit. The score in each language is the number of correct responses. Vocabulary scores from both languages were used as predictors for the frequency effect in L2.

Lexical decision task. Each participant performed two versions of a lexical decision task, one in Hebrew (L1) and one in English (L2). Each task included 60 target words and 60 non-words. Targets ranged in frequency between 1.55 and 420.61 per million (see corpora information below).

English target words were taken from the stimuli in Gollan et al. (2011), which included 90 nouns, half high-frequency and half-low frequency based on a standard frequency corpus (Time Magazine Corpus, Davies, 2007). This corpus includes 100 million tokens taken from written magazine text. We pre-tested the words in a lexical decision task to make sure that our study population, who are L2 English speakers, was indeed familiar with the experimental items. Eighteen undergraduates from the University of Haifa (who did not participate in the main experiment) completed the pre-test. Words that were not correctly identified in the pre-test by at least 80% of participants, were not included in the main study. Hebrew–English cognates were also eliminated from the list.

Hebrew target nouns were selected to match the English target nouns described above, in terms of frequency and length (see below). Frequency counts for the Hebrew nouns were based on the heTenTen 2014 corpus via Sketch Engine (Kilgarriff, Rychlý, Smrž, & Tugwell, 2004). This corpus includes 890 million words extracted from the internet. The Hebrew nouns were matched to the English list in frequency count and length in phonemes (see Table 1 for target words characteristics), but not in length in letters because most vowel letters are omitted in the written form of Hebrew. Since length in letters has an influence on word recognition reaction time (RT) (e.g. New, Ferrand, Pallier, & Brysbaert, 2006), this factor is treated as a control variable in our study.

Table 2. Participant characteristics: mean (standard deviation); and range.

Age (years)	25.03 (3.31), 18–36	
Education level (years)	13.9 (1.7), 12–17	
	Hebrew	English
Age of language acquisition	–	9.23 (1.77), 5–19
Self-rated oral language proficiency*	9.61 (0.6), 7.5–10	6.97 (1.76), 1–10
Reading fluency*	81.79 (10.79), 57.69–100	72.88 (9.65), 50.96–96.15
Vocabulary knowledge*	70.91 (14.93), 30–95	50.26 (12.2), 27.5–80
Self-rated language exposure*	8.44 (1.22), 5.6–10	4.24 (1.68), 0.4–8.6

Note: reading fluency = % of words correctly read in 45 seconds (Test of Word Reading Efficiency); self-rated oral language proficiency = an average score of two measures: oral language comprehension and production, on a 1–10 scale (Language Experience and Proficiency Questionnaire (LEAP-Q)); vocabulary knowledge = % correct (Shipley test); self-rated language exposure = an average score of five measures: current exposure to English in audio, television, reading, family setting, and social setting, on a 1–10 scale (LEAP-Q).

*the means of native language and second language are significantly different, $p < 0.001$.

In both languages, the non-words were created by replacing one or two letters of target words.

In each trial of the lexical decision task, a fixation point appeared in the center of the screen for 500 milliseconds (ms) and was replaced by a word or a non-word, which remained on the screen until the participant responded by button press. Participants were instructed to respond as quickly and accurately as possible. Eight practice items preceded the experimental list.

Visual Statistical Learning Task

The VSL task (Siegelman, Bogaerts, & Frost, 2017a), includes a familiarization phase, immediately followed by a test phase. The stimuli consist of 16 abstract shapes, randomly organized for each participant into eight triplets (four triplets with transitional probabilities of 0.33, and four triplets with transitional probabilities of 1). During the familiarization phase, each shape is presented to the participant for 800 ms, followed by a 200 ms interstimulus interval. During this stage, each triplet appears 24 times, in random order. The test phase consists of 32 recognition items and eight completion items, resulting in a maximum score of 42 for each participant (for a detailed description of the task and a review on its reliability, see Siegelman et al., 2017a). VSL scores were used as predictors of the frequency effect in L2. Chance performance on this task is 16.7 correct answers (Siegelman et al., 2017a).

Procedure

Participants were tested individually in a single session lasting one hour. Participants first completed the lexical decision task in both languages (language order counterbalanced across participants). Next, participants were tested in the VSL task, followed by the reading fluency tests (TOWRE) and the vocabulary knowledge test (Shipley) in L1 and L2, also counterbalanced across participants. Finally, participants completed the LEAP-Q. Participants were offered breaks between tasks.

Results

Participant characteristics are presented in Table 2. As expected, there were significant differences between participants' L1 and L2 abilities, indicating higher exposure and proficiency scores for Hebrew (L1) than for English (L2).

Table 3. Linear mixed-effects interactive model predicting reaction times in native language and second language lexical decision.

Fixed effects	Estimate	Standard error	t-value	p-value
(intercept)	637.439	39.849	15.996	< 0.001
Language	-166.377	24.599	-6.764	< 0.001
Word frequency	-149.545	17.609	-8.492	< 0.001
Language * word frequency	115.450	23.659	4.880	< 0.001
<i>Control variable</i>				
Word length in letters	24.757	6.426	3.852	< 0.001
<i>Random effects</i>				
	Variance	Standard deviation		
Word (intercept)	3535	59.45		
Participant (intercept)	23695	153.93		
Language	27373	165.45		
Word frequency	1421	37.69		

Performance was analyzed using linear mixed-effects (LME) models (Baayen, Davidson, & Bates, 2008) in R (R Core Team, 2018), with the lme4 library (version 1.1-7, Bates, Maechler, Bolker, & Walker, 2015). Plots were created using the ggplot2 package (version 2.3.00) (Wickham, 2016). The *p*-values were derived using Satterthwaite approximations of degrees of freedom in the lmerTest function, an approach found to produce acceptable Type 1 error rates (Luke, 2017).

Mean RTs to correct responses in the lexical decision task were analyzed. Responses faster than 300 ms or slower than 3000 ms were excluded (0.002% of the correct responses). Task performance was highly accurate in both languages (in Hebrew 97%, ranged 90–100%; in English 93%, ranged 72–100%), and so accuracy rates are not further analyzed (Smith, Walters, & Prior, 2019).

Frequency effects in L1 and L2

The model included the following fixed factors: language (Hebrew, English) which was a categorical factor, with English set as the reference; word frequency (continuous) which was log transformed to normalize the distribution and centered; and word length in letters was included as a control variable (continuous). The model included a maximal random effect structure (Barr, Levy, Scheepers, & Tily, 2013), with random intercepts by items and by participants, and random slopes for language and log frequency by participant. We first ran an additive model including only language and frequency as predictors, then followed by an interactive model, which added the interaction of language and frequency as a predictor. The interactive model was found to fit the data significantly better than the additive model ($\chi^2 = 22.268$, $df = 1$, $p < 0.0001$), and thus we only report its results in Table 3.

Both effects and the interaction were significant. The main effect of language indicated faster responses for L1 than for L2. The main effect of word frequency indicated faster responses for higher frequency words than for lower frequency words. The interaction between language and word frequency revealed a larger frequency effect in L2 than in L1 (see Figure 1), even after controlling for the main effect of word length (which revealed faster responses for shorter words than for longer words).

Individual differences: What predicts the L2 frequency effect?

To analyze individual differences, we ran an LME model to predict lexical decision RTs to L2 words only. We examined the possible role of the following predictor variables: L2 vocabulary

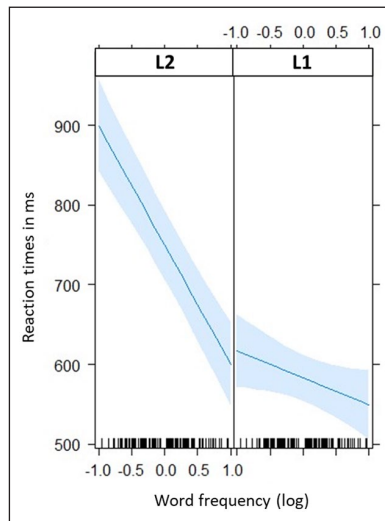


Figure 1. Frequency effect in native language (L1) and second language (L2). The effect of word frequency (log-transformed and centered) on participants' lexical decision reaction times (milliseconds), in their L1 (Hebrew) and L2 (English).

knowledge; L2 exposure; and L1 vocabulary knowledge. In addition, we calculated for each participant their sensitivity to frequency in L1 lexical decisions, as expressed by the correlation (slope) between word frequency and RT in L1. Finally, accuracy of performance on the VSL task was also included as a predictor. Performance in this task was similar to that reported in previous studies (Siegelman et al., 2017a, mean = 22.15, standard deviation = 5.79, range 11–35). Pairwise correlations between the predictor variables were overall low (all $r < 0.29$), and none were significant following Bonferroni correction for multiple correlations, which set the significance level at 0.005 (all $ps > 0.02$, see Appendix for full details). We thus felt confident in entering the predictor variables independently in the model.

Because we were interested in whether the investigated variables might modulate the frequency effects across participants, the effects of interest in the current model were possible interactions between each of these predictors and word frequency in the L2. The random structure of the model included intercepts for participants and items, as well as the random slope for log frequency by participants, and for L2 vocabulary knowledge per item (fuller random structures failed to converge). Once again, word length was included as a control variable.

The results are presented in Table 4. The model indicated significant main effects of word frequency and L2 vocabulary knowledge, indicating that higher word frequency (of items) and larger L2 vocabulary knowledge (of participants) predicted faster RTs. It is worth noting that we found a marginal main effect for L1 vocabulary knowledge, indicating that participants with larger L1 vocabulary knowledge also tended to have overall faster RTs in the L2 lexical decision task. Most importantly, to test our theoretical question regarding individual difference variables that might modulate participants' sensitivity to frequency in the L2, we found a significant interaction only between word frequency and L2 vocabulary knowledge, such that participants with larger L2 vocabulary knowledge had significantly smaller L2 frequency effects (see Figure 2). All remaining predictors and interactions were not significant.

Table 4. Linear mixed-effects model predicting reaction times in second language (L2) lexical decision.

Fixed effects	Estimate	Standard error	t-value	p-value
(intercept)	1097.6257	145.5101	7.543	< 0.01
Word frequency	-308.2712	92.2497	-3.342	< 0.01
L2 vocabulary knowledge	-6.1188	1.8363	-3.332	< 0.01
L2 self-rated exposure	-19.7887	12.7849	-1.548	Not significant (NS)
Native language (L1) vocabulary knowledge	-2.5305	1.4588	-1.735	0.0879
L1 frequency slope	202.5613	124.4712	1.627	NS
Visual statistical learning (VSL) performance	3.6770	3.7530	0.980	NS
Word frequency * L2 vocabulary knowledge	3.0909	1.2128	2.549	< 0.01
Word frequency * L2 self-rated exposure	6.2875	7.3465	0.856	NS
Word frequency * L1 vocabulary knowledge	0.2595	0.8321	0.312	NS
Word frequency * L1 frequency slope	-34.5488	70.5959	-0.489	NS
Word frequency * VSL performance	-2.1989	2.1424	-1.026	NS
<i>Control variable</i>				
Word length in letters	35.4296	8.7017	4.072	< 0.001
<i>Random effects</i>				
	Variance	SD		
Word (intercept)	12365	111.20		
L2 vocabulary knowledge	192.8	13.88		
Participant (intercept)	24411	156.24		
Word frequency	3940	62.78		

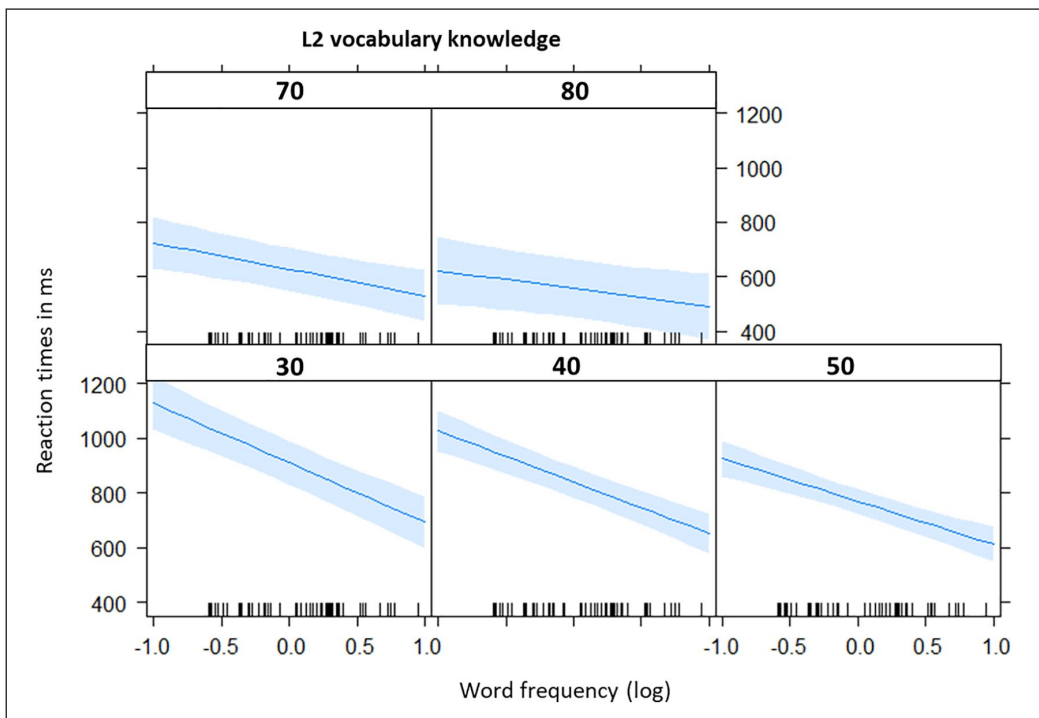


Figure 2. Second language (L2) frequency effects by L2 vocabulary knowledge.

Discussion

In the current study, we adopted an individual differences approach to investigate efficient L2 word reading, as manifest in the L2 frequency effect. Specifically, we probed the possible contributions of L2 exposure and vocabulary, L1 vocabulary and frequency effects, and general sensitivity to non-linguistic regularities. We chose to investigate this issue in a population of unbalanced Hebrew–English bilinguals, who speak typologically different languages that do not share a writing system, in order to examine how well patterns previously reported for bilingual speakers of closely related languages might generalize. Results revealed that only L2 vocabulary knowledge predicted individual differences in the L2 frequency effect.

L2 vocabulary knowledge

In the current study, frequency effects in L2, participants' less proficient language, were significantly larger than in L1. In addition, individuals' L2 vocabulary knowledge proved to be important for understanding variability in the impact of word frequency on lexical decision performance in L2. Specifically, participants who had higher scores on the L2 vocabulary test, demonstrated smaller frequency effects in L2.

Early studies suggesting the role of L2 proficiency in reduced L2 frequency effects in lexical decision tasks relied on comparing groups reading in the same language, that was either their L1 or L2 (Duyck et al., 2008; Gollan et al., 2011). These studies indeed reported larger frequency effects for L2 than for L1 readers. More recently, three studies investigating individual differences have also found that larger vocabulary knowledge or exposure is associated with smaller L2 frequency effects in a lexical decision task (Brysaert et al., 2017; Diependaele et al., 2013) and in reading times (Whitford & Titone, 2012). The current results reinforce and support this pattern, since we found that L2 vocabulary knowledge significantly modulated the effect of word frequency on reading times.

Thus, the current pattern of results aligns well with the theoretical suggestions made by the frequency-lag hypothesis (Gollan et al., 2011) and the lexical entrenchment approach (Brysaert et al., 2017; Diependaele et al., 2013). Our findings, therefore, reinforce the notion that reduced exposure/proficiency, but not cross-language competition, are most likely the reason for increased L2 frequency effects in general.

The previous studies examining individual differences (Brysaert et al., 2017; Diependaele et al., 2013) included objective tests of vocabulary knowledge, under the assumption that vocabulary knowledge mostly reflects language exposure (see also Kuperman & Van Dyke, 2013), though exposure was not directly assessed. Whereas we agree that this assumption is valid when comparing L1 and L2 speakers, it might not generalize as well to individual variability within L2. In the current study, we collected participants' self-reported exposure and an objective vocabulary test, and somewhat surprisingly did not find a significant correlation between them (though see Tomoschuk, Ferreira, & Gollan, 2018, for similar findings regarding self-rated proficiency). Further, self-reported L2 exposure did not uniquely predict variance in L2 response times or frequency effects. We therefore suggest some caution in treating vocabulary knowledge as a straightforward indicator of language exposure (e.g. Brysaert et al., 2017). In contrast, the current finding supports the notion that even given a similar level of language exposure, different learners might acquire vocabulary at different rates (e.g. Robinson, 2003; Van Patten, 2015). This is especially true for non-novice learners, such as the intermediate proficiency population of the current study. Thus, we reinforce the importance of wide-range and valid measures of vocabulary knowledge, in addition to self-reports of exposure, as critical tools in research comparing monolingual and bilingual language processing (Brysaert et al., 2017).

General language abilities as expressed in L1 vocabulary

Although the studies described above did not examine the possible contribution of L1 abilities to L2 frequency effects, closely related research measuring eye-movements in reading has started to address this issue. Thus, in a previous study examining individual differences in L2 frequency effects among Dutch–English bilinguals, participants' L1 vocabulary knowledge was found to be a significant predictor (Cop et al., 2015). Specifically, participants who had higher vocabulary knowledge in the L1 tended to have smaller frequency effects in the L2. The authors suggest that L1 vocabulary knowledge can be interpreted as reflecting general language processing or learning abilities, within their population of fairly homogenous university students, with arguably similar levels of exposure to the native language.

In contrast, the current study did not find L1 vocabulary knowledge to be a significant predictor of L2 lexical decision times or frequency effects when examining Hebrew–English bilinguals. We offer two possible explanations for this divergence of results. The first and more likely possibility is that this divergence in results across studies is a consequence of the specific bilingual population tested in each of the studies. Participants in the current study are bilingual speakers of two typologically and orthographically distant languages, whereas participants in Cop et al. (2015) spoke Dutch and English, which have significant typological similarity. Moreover, Dutch and English share an alphabet and have an unavoidable overlap in some vocabulary items, due to cognates and interlingual homographs (Diependaele et al., 2013; Lemhöfer et al., 2008; Schepens et al., 2012). In this case, as demonstrated in the computational model by Monaghan et al. (2017), accessible knowledge about words from the L1 might be transferred to the L2. Thus, although Cop et al. (2015) excluded cognates and interlingual homographs from their analysis, arguably knowledge of L1 Dutch can play a stronger role in predicting performance of L2 English than knowledge of L1 Hebrew can.

An alternative, or additional, explanation is that Cop et al. (2015) examined frequency effects in reading times using eye-tracking measures, whereas the current study used a lexical decision task. Recent evidence suggests that the two types of reading measures might be relatively weakly correlated with each other (Dirix, Brysbaert, & Duyck, 2018; Kuperman et al., 2013). Thus, it is possible that the language abilities captured by L1 vocabulary knowledge might relate more strongly to L2 frequency effects as manifest in contextual reading than in an isolated, less natural, single word lexical decision task.

The discrepancy between the current results and those obtained by Cop and colleagues (2015), suggests that future research should further investigate the possible contribution of general language abilities, as reflected in L1 vocabulary knowledge, to the quality of L2 lexical representations. Further, it stresses the importance of examining bilinguals of diverse profiles especially in regard to typological distance and overlap of orthographic systems, or lack thereof (as also recently suggested by Jiang, 2019; Mishra, 2019; Van Heuven & Wen, 2019).

L1 frequency effects

In the current study we hypothesized that the magnitude of the L1 frequency effect, as a measure of readers' general ability to create high quality lexical representations, might explain variance in L2 frequency effects, but this was not borne out by the data. Specifically, participants' slope of the correlation between frequency and RT in Hebrew, did not interact significantly with frequency in predicting RTs to L2 words. Although null effects can only be interpreted with some caution, the current pattern of results might suggest that the mechanisms supporting the creation of lexical representations that is shared across L1 and L2 might only partially overlap with each other.

Further, it might be the case that the relation between frequency effects in L1 and L2 depends on typological and orthographic similarity between the languages, as suggested above for the effect of L1 language proficiency more generally. Thus, especially for speakers of Hebrew and English, who might show qualitative differences in the principles governing lexical organization (e.g. the importance of morphology, see Frost, Deutsch, & Forster, 1997; Kolan, Leikin, & Zwitserlood, 2011; Prior & Markus, 2014), the process of creating high quality lexical representations might be relatively language specific. Certainly, this suggestion is speculative at this point, and again requires further investigation of different and varied bilingual populations to gain a fuller understanding of this issue.

Visual statistical learning

The current study also included a measure of visual statistical learning, in light of much recent interest in the literature regarding its possible contribution to second language processing and reading (Brooks et al., 2017; Frost et al., 2013). However, in the current sample, performance on the VSL task was not associated with the sensitivity to word frequency in the L2. Moreover, VSL scores did not correlate with any of the investigated variables, in either L1 or L2, despite some previous reports of links between statistical learning abilities and different aspects of language processing, in L1 (Conway et al., 2010; Evans et al., 2009; Misyak & Christiansen, 2012; Spencer et al., 2015) or in early stages of L2 learning (Brooks et al., 2017; Frost et al., 2013; Kaufman et al., 2010; Onnis et al., 2016)¹.

One possible explanation recently put forth by Siegelman, Bogaerts, Christiansen, and Frost (2017b), is that rather than being a unified and single mechanism underlying a wide range of learning and processing abilities, statistical learning is better understood as a set of separate components. That is, it might be the case that the learning mechanism underlying performance in the specific VSL task used in the current study, recruits different processing resources than those underlying the performance of the linguistic measures of the study, an issue which should be further explored in future research. Alternatively, it is also possible that the process of creating high quality lexical representations in L2 is mostly distinct from readers' general sensitivity to distributional patterns of co-occurrence in the non-linguistic domain, and is better conceptualized as a skill that is mostly domain- or even language-specific.

Conclusion

The current study reinforces the notion of frequency effects as a marker of efficient visual word processing in the L2. Our results align with the theoretical claims of the frequency-lag (Gollan et al., 2011) and lexical entrenchment (Brysbaert et al., 2017; Diependaele et al., 2013) hypotheses, by identifying L2 vocabulary knowledge as a significant and only predictor of individual differences in L2 frequency effects. Importantly, L2 vocabulary knowledge significantly predicted frequency effects, whereas self-reported exposure did not. This finding attests to the importance of high-quality lexical representations for less frequent words as driving reduced frequency effects, beyond exposure itself as a lexicon-external variable. The significant role of L2 vocabulary knowledge stands out for two reasons. First, we did not find L1 proficiency to predict L2 frequency effects, most likely due to the pronounced cross-linguistic typological and orthographic distance between the L1 and L2 investigated in the current study. Second, two novel predictors indexing more general learning and processing mechanisms, namely L1 frequency effects and visual statistical learning, were not associated with L2 frequency effects. Although such null effects should be interpreted cautiously, this pattern of results suggests that at least when L2 is very different from

L1, readers' ability to create high quality lexical representations is mostly language specific and might not recruit L1 or domain general skills. The degree to which this description might also apply to other types of bilinguals can only be determined by future studies.

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Note

1. It is possible that studies *not* finding a significant link between statistical learning and language performance might be less likely to reach publication (a manifestation of the “file-drawer” problem).

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Appendix. Correlation matrix of the predictor variables.

	2.	3.	4.	5.
1. Second language (L2) vocabulary knowledge	0.265	0.108	0.288	0.143
2. L2 self-rated exposure		0.072	–0.083	0.274
3. Native language (L1) frequency effect			0.134	0.01
4. L1 vocabulary knowledge				0.288
5. General sensitivity to regularities (visual statistical learning)				

Note: following Bonferroni correction for multiple correlations, significance level was set at 0.005 – none of the correlations were significant.