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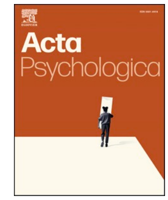

Neighborhood frequency effects in late bilingual phonological neighborhoods

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A B S T R A C T

The bilingual mental lexicon is understood as a unified system containing word forms from multiple languages. Previous studies have described how cross-language phonological similarity influences bilingual lexical processing, demonstrating that lexical activation spreads both within and across languages at the segmental level. The significance of cross-linguistic phonological neighbors in bilingual speech processing is well documented, but less is known about frequency effects emerging from the cross-language neighboring words. In monolingual spoken word recognition, the 'neighborhood frequency effect' suggests that higher-frequency neighbors absorb more activation and/or inhibit lower-frequency neighbors within a phonological neighborhood, potentially affecting recognition latencies. This study examines whether this effect extends across languages in phonological neighborhoods of late German-English bilinguals. Results reveal that lexical frequency rates of German neighbors influence response times for English target words in an English lexical decision task. This finding supports a fully integrated mental lexicon in late bilinguals (i.e., second language learners) and highlights the role of lexical frequency in cross-language lexical processing.

1. Introduction

Spoken words tend to be recognized faster when lexical competition is reduced by having fewer phonologically similar words in a speaker's mental lexicon (Luce & Pisoni, 1998; Vitevitch, 2007; Vitevitch et al., 2018; Vitevitch & Luce, 2016; Yates & Dickinson, 2023; Ziegler et al., 2003). This effect has primarily been studied from the viewpoint of phonological neighborhood density, a metric that considers the number of phonologically close words that exist in a lexicon. Traditionally, psycholinguistics has defined phonological neighbors as words differing by a single phonological segment, the Levenshtein distance (Landauer & Streeter, 1973; Levenshtein, 1966; Vitevitch & Luce, 2016), even though alternative quantifications of phonological neighborhoods can be found in the literature (Kapatsinski, 2006; Siew & Castro, 2023; Vitevitch & Castro, 2015). Within the framework of activation spreading (Luce et al., 2000; Vitevitch & Luce, 1998; Yates & Dickinson, 2023), it is theorized that phonological overlaps between words lead to co-activation of shared segments. When a word has numerous phonological neighbors, activation is distributed among them, creating a delay in the recognition of the target word within the neighborhood (Vitevitch & Luce, 2016). A higher density of phonological neighborhoods reduces the activation allocated to each individual word and leads to lower overall activation of each word, including the target word itself. While this effect can be seen as passive activation sharing across lexical candidates, theoretical accounts of active lexical competition, where an active item inhibits its neighbors, are also frequently encountered (Goldinger et al., 1989; Vitevitch & Luce, 2016; Yates & Dickinson, 2023). Chen and Mirman (2012) model activation spreading as a trade-off between inhibitory and facilitative links between lexical neighbors, where strongly activated words have an inhibitory effect and weakly activated neighbors have a facilitative effect on word recognition. Activation spreading is then dependent on how much inhibition and facilitation there is within a neighborhood. The influence of phonological neighborhood density on word recognition is well-supported by monolingual studies (see Yates & Dickinson, 2023, for a review); similar effects have been observed in multilingual studies (de Bot & Batyi, 2022; Kroll & Ma, 2017). Bilingual speakers, especially those using typologically related languages with significant word form similarities (e.g., Germanic languages, such as English, German, Dutch), experience increased activation spreading in bilingual phonological neighborhoods, as words from multiple languages become lexical competitors (e.g., Canseco-Gonzalez et al., 2010; Dijkstra et al., 2010; Frances et al., 2021; Lagrou et al., 2011; Lemhöfer

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et al., 2008; Luef, 2025a; Marian et al., 2008; Schulpen et al., 2003). Theoretical accounts of cross-linguistic activation spreading in spoken word recognition (Lewy & Grosjean, 2008; Schwartz & Kroll, 2007; Shook & Marian, 2013) predict that lexical activation propagates through sublexical features and across languages of multilingual individuals, ultimately leading to competition effects at the lexical level (Vitevitch & Luce, 1998, 1999). This means that cross-language phonological neighbors, such as English *climb* [klaɪm] and German "Leim"/ Engl. *glue* [laɪm], have a similar effect to same-language neighbors within their neighborhoods (Luef, 2025a).

The impact of activation spreading within phonological neighborhoods is modulated by the frequency of the segments and words (Luce & Large, 2001; Vitevitch & Luce, 1999), with more frequently occurring items showing higher degrees of activation. Whether lexical frequency is defined according to resting activation level (Dell, 1986; Luce & Pisoni, 1998), or whether it is seen as connection weights between a lexical representation and its segments (Chen & Mirman, 2012), higher frequency words are activated more strongly and faster, leading to shorter response latencies in word recognition. The higher baseline activation of frequent words in linguistic memory leads to less cognitive effort for their retrieval (Belke et al., 2005; Borowsky & Masson, 1999). Lexical frequency effects are commonly explained by learning effects, assuming that learning increases activation levels of word representations (Brysbaert, Mandera, & Keuleers, 2017; Coltheart et al., 2001). Alternatively, frequency effects may be considered as confounds of other lexical features such as word length and age of acquisition (Brysbaert, Mandera, & Keuleers, 2017), as these variables are typically highly correlated in first (Brysbaert & Biemiller, 2016; N. C. Ellis, 2002; Frauenfelder et al., 1993; Storkel et al., 2006) and second (Luef, 2023) languages.

While lexical frequency plays a central role in models of spoken word recognition (e.g., Neighborhood Activation Model. TRACE), with its effects on word recognition well attested in different languages (e.g., Brysbaert et al., 2011, 2019; Brysbaert & New, 2009; Ferrand et al., 2010), little attention has been paid to frequency effects arising not from the target word but the neighboring words in a phonological neighborhood. Frequencies of neighboring words can have varying degrees of influence on word recognition. According to a passive lexical competition account in phonological neighborhoods, high-frequency words are suggested to constitute stronger competitors as they absorb more of the present activation (Luce & Pisoni, 1998). This diverts activation away from lower-frequency words. Depending on the frequency rate of a target word, it may be affected in different ways: if neighbors are of higher lexical frequencies than the target word, they take more of the activation, resulting in slower response latencies to the target; if target words show the highest frequency rates, they are not predicted to be delayed. Alternatively, higher-frequency words may inhibit activation of lower-frequency words, resulting in higher-frequency words monopolizing a larger share of the activation within a neighborhood. Regardless of the activation mechanics, the "neighborhood frequency effect" manifests as the influence of the frequency of phonological neighbors on the speed and accuracy with which a spoken word is recognized (Andrews, 1989; Frauenfelder et al., 1993).

Neighborhood frequency effects play a central role in various cognitive linguistic tasks, including perceptual identification (Dirks et al., 2001; Pisoni et al., 1985), where word identification is typically superior when target words themselves are of higher lexical frequency but the neighborhood consists of low-frequency words. Neighborhood frequency effects are also crucial determiners for word memory, and in particular short-term memory. High-frequency words in sparse, low-frequency neighborhoods tend to be more easily recalled than low-frequency words in dense, high-frequency neighborhoods (Goldinger et al., 1991; Roodenrys et al., 2002), demonstrating an active role of neighborhood frequency on lexical memory. Furthermore, neighborhood frequency effects emerge in picture naming (Baus et al., 2008; Vitevitch & Sommers, 2003, but note the difference in the suggested direction of the effect), speech errors (Vitevitch, 1997), as well as speech production in first language acquisition (Newman & German, 2002). Further underscoring the importance of the neighborhood frequency effect in word recognition are studies on phonological false memories (Roediger & McDermott, 1995; Sommers & Lewis, 1999). When asked to recall a list of phonologically neighboring words, higher frequency neighbors tend to be mis-selected (e.g., falsely remembering "line" instead of "lime"). In sum, neighborhood frequency effects influence phono-lexical processing on various dimensions, making them an important aspect of lexical cognition.

The majority of existing studies on the neighborhood frequency effect in lexical processing investigated speech production and visual word recognition. Studies on spoken word recognition include Luce and Pisoni (1998) who found that higher-frequency neighbors raise lexical competition because they raise the overall level of activity within a neighborhood, where multiple similar words are activated at the same time, making it harder to settle on the correct target word. Thus, a high-frequency neighborhood causes recognition delays in target words. Similar findings for French were reported by Dufour and Frauenfelder (2010). Furthermore, accuracy of word judgment seems to be affected negatively by the presence of high-frequency neighbors in Spanish phonological neighborhoods (Cervera-Crespo & Gonzalez-Alvarez, 2019).

Not all studies of auditory word recognition have come to the same conclusion (e.g., Forster & Shen, 1996; Hameau et al., 2021; Sears et al., 1995, 2006; Wagenmakers et al., 2008), and in the word production domain, the opposite findings are well established: high-frequency neighbors actually facilitate target word retrieval in English and Spanish (e.g., Vitevitch & Luce, 2016; Vitevitch & Sommers, 2003). This reflects the different demands of the two modalities perception and production.

Concerning bilingual word recognition, no studies to date have specifically focused on neighborhood frequency effects resulting from cross-language neighbors. The present study was designed to shed light on this issue and determine whether spoken word recognition of English-as-a-second-language (or "L2") is influenced by German-as-a-first-language (or "L1") in late bilinguals. The findings will provide cues as to the complexity of lexical processing in speakers of multiple languages.

1.1. Patterns of bilingual phonological neighborhoods

Since activation spreads along phonological segments, phonological similarity is a crucial consideration (Gahl & Strand, 2016; Luef, 2023, 2025a). It has been proposed that closer neighbors constitute stronger competitors to target words than more distant neighbors (e.g., Chen & Mirman, 2012; Mirman & Kittredge, 2010), attributing phonological similarity major influence on spoken word recognition in mono- and bilingual studies. The one-segment neighbor metric between word forms (i.e., Levenshtein distance) can be quantified based on more nuanced measures that weigh individual phonological features (e.g., frontness, nasality, etc.; see section 3.6 for more details), resulting in phonological neighborhood patterns that consider phonological closeness between word forms that differ by one phonological segment.

A key factor in frequency effects is the overall frequency distribution within a phonological neighborhood. If the target word has the highest lexical frequency rate, the neighborhood is predicted to have less influence on recognition compared to cases where neighbors have higher lexical frequencies. Figs. 1 and 2 illustrate different frequency distributions within bilingual phonological neighborhoods, which are expected to lead to different response latencies for the English target words. The recognition of both "hint" and "fly" is assumed to be influenced by the lexical frequency rates of their respective neighbors and the phonological similarity of word forms, regardless of the language. Because "hint" is a low-frequency word with English neighbors that are both lower in frequency and less phonologically similar (indicated

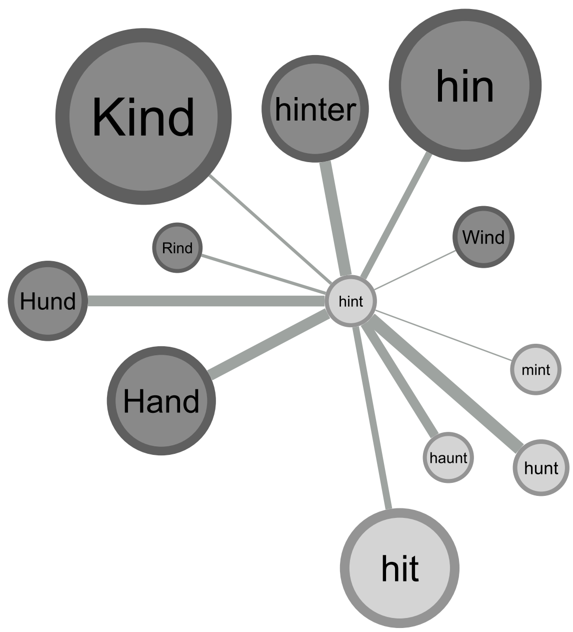

Fig. 1. A representation of the phonological neighborhood of English "hint". Dark nodes represent German phonological neighbors; light-gray nodes represent English phonological neighbors. Node size corresponds to lexical frequency rate. The L2-English neighbors (CEFR proficiency level C1) are generally of lower lexical frequency, while the cross-language L1-German neighborhood contains various high-frequency words as well as closer phonological neighbors (indicated via line strength).

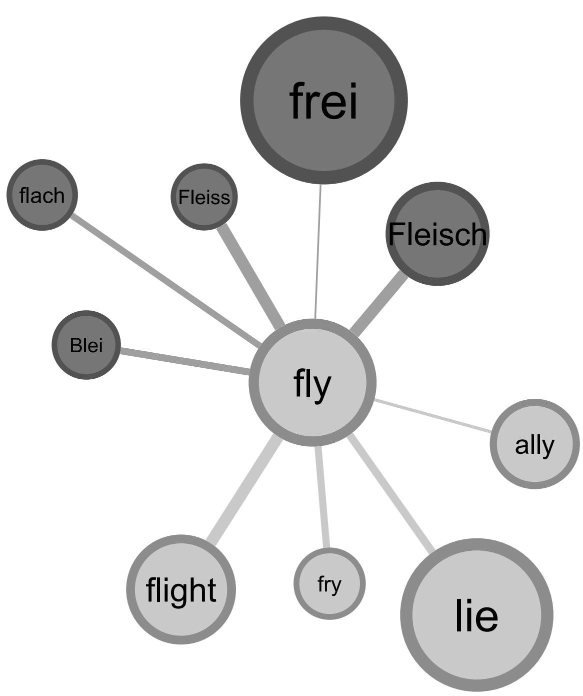

Fig. 2. A representation of the phonological neighborhood of English "fly". Dark nodes represent German phonological neighbors; light-gray nodes represent English phonological neighbors. Node size corresponds to lexical frequency rate. The L2-English neighbors (CEFR proficiency level C1) and the L2-English neighbors are of similar lexical frequency as the L1-German neighbors. The higher-frequency English neighbors are phonologically similar to the target (indicated via line strength).

through thinner links), it is expected to be more affected by high-frequency, phonologically closer German neighbors. In contrast, "fly" is phonologically more distant from its highest-frequency neighbor (German "frei" / Engl. *free*) and is therefore expected to be more strongly influenced by higher-frequency and phonologically closer English neighbors such as "lie" and "flight".

Bilingual phonological neighborhoods can vary in complexity based on phonological similarity and frequency patterns in each language-specific section of a neighborhood. Recent methodological advances in lexical sciences have introduced the innovative approach of studying the mental lexicon as a lexical network, emphasizing the interconnected nature of word forms (see Fig. 3). The position of target words within these lexical networks have been shown to influence lexical processing. This includes factors such as density of a network region (Siew & Vitevitch, 2016), the interconnectedness of the phonological neighborhood (Chan & Vitevitch, 2009; Luef, 2025a; Yates, 2013), and the key structural positions held by target words in a lexical network (Goldstein & Vitevitch, 2017; Vitevitch & Goldstein, 2014). In bilingual phonological networks, such as the L1-German-L2-English one shown in Fig. 3, the frequency distribution of neighbors in each individual language, as well as within the integrated bilingual lexicon, is a critical factor to consider.

Fig. 3 illustrates the variability of phonological neighborhoods (and their extended neighborhoods) in terms of the number of neighbors, their phonological similarity, and lexical frequency (which corresponds to node size in Fig. 3). It is evident that not all neighbors have the potential to exert the same influence, and lexical processing largely depends on the specific phonological and frequency composition of a given neighborhood. The spread of co-activation can be predicted by the number of neighbors, phonological similarity between target words and neighbors, neighborhood frequency relative to target word frequency, and the integration of English and German word forms in bilingual lexica. Phonological network science provides a valuable framework for controlling these variables, thereby aiding the study of spoken word recognition.

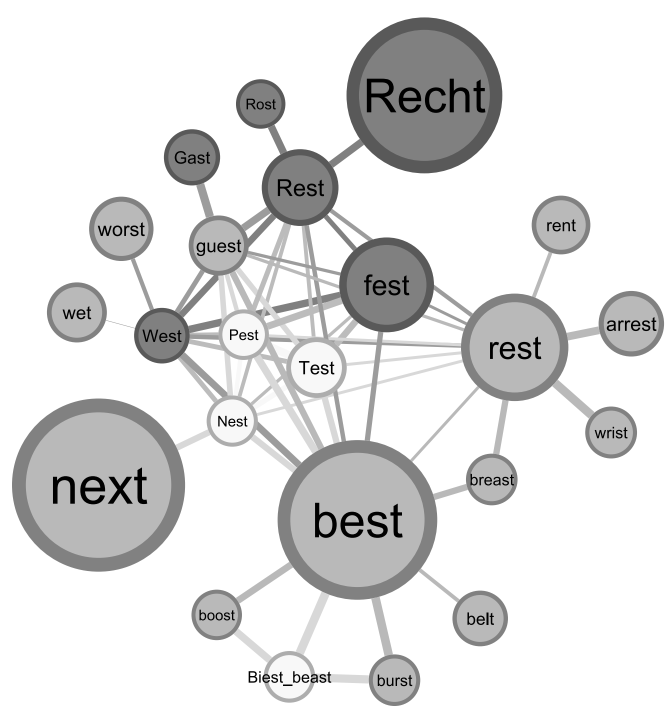

Fig. 3. Partial bilingual phonological network. Light-gray nodes represent L2-English words (CEFR proficiency level C1), dark nodes represent L1-German words, white nodes represent word forms shared by both languages. Node size corresponds to lexical frequency rate. Link strength corresponds to phonological similarity.

This study aims to broaden the scope of research on the neighborhood frequency effect by studying it from a bilingual perspective. The research question explored here concerns the influence of lexical frequency of German phonological neighbors on L2-English target words. Are German neighbors and their lexical frequency rates predictive for the retrieval of English target words? Based on the assumption that German neighbors play a significant role in bilingual word recognition, it is hypothesized that word recognition will be delayed by high-frequency German neighbors within the neighborhood, due to their effect on activation spreading.

Understanding the interactions between languages in multilingual speakers allows crucial insights into lexical cognition, particularly given the growing proportion of multilingual individuals in European societies and beyond (Siemund, 2023). Dynamics of activation spreading in bilingual phonological neighborhoods serve as key evidence for an integrated mental lexicon in multilinguals. If bilingual lexical processing is driven by activation strength and the depth of memory representations shaped by lexical frequency in the dominant (first) language, this could offer new perspectives on activation spreading in second language cognition. Such findings can contribute to models of bilingual lexical organization.

2. Data availability

The data and code for replication of the results can be found in the Supplementary Material and on the Zenodo repository under the link: https://doi.org/10.5281/zenodo.17431193.

3. Methods

German-English late bilinguals were tested in auditory word recognition in various experimental conditions that varied the frequencies of the German neighborhoods of the English target words. Based on previous monolingual studies of neighborhood frequency effects in spoken word recognition, it was expected that higher-frequency neighbors that are phonologically more similar to the target words would lead to longer response latencies as more lexical activation is incorporated by those neighbors.

In a first step, a bilingual phonological lexicon that combines L1-German and L2-English was constructed. Under consideration of various network metrics, a number of target words were selected and controlled for additional factors (see section 3.6.). As a second step, participants were tested in their knowledge of all target words as well as all neighboring words that were identified in the network model. Lastly, the target words were tested in an auditory lexical decision task, which measured accuracy of word judgments as well as reaction times to the English target words.

3.1. Phonological networks

The L1-German vocabulary was based on data obtained from the *SUBTLEX-DE Corpus* (Brysbaert et al., 2011), a corpus of German subtitles in film and TV, that is available on the Clearpond database (Marian et al., 2012). It is considered one of the best frequency measures for undergraduate student speech (Brysbaert & New, 2009). The English vocabulary was obtained from the *English Vocabulary Profile* database, which is a collection of L2- English vocabulary based on the *Cambridge Learner Corpus*, the largest corpus of English as a second language (Capel, 2015). Vocabulary corresponding to proficiency level CEFR-C1 was used (see below for a description of CEFR proficiency levels).

In both vocabularies, proper nouns were removed and lemmatization was applied to remove the majority of inflections. Only extremely high-frequency inflected forms were retained, such as inflections of the English words "be" and "have" and the German correspondences "sein" and "haben" and participle II forms which can function as adjectives (German "gemacht"/ *Engl. "done"*). German inflections related to grammatical gender of nouns (e.g., "Arzt-Ärztin"/ *Engl. male doctor-female doctor*) were also retained. Clitics were split into their constituent parts (e.g., English "it's" ➔ "it", "is"; German "aufs" ➔ "auf", "das"/ *Engl. "on the"*).

In German, infrequent loan words and compound nouns consisting of English and German words (e.g., "Actionszene"/ *Engl. "action scene"*) were removed. Additionally, specific medical vocabulary and abbreviations (e.g., "Dino"/ *Engl. "dinosaur"*) were excluded from the data, as well as swear words and numbers larger than 12 and not multiples of 10. Lemmatized German words that were not contained in the SUBTLEX-DE corpus were removed from the dataset ($N = 414$ words, 3.7.% of the German vocabulary). This was necessary because lexical frequency rates of the German words were obtained from that corpus (i.e., via the Clearpond database). All lemmatized English word forms of the C1-English vocabulary could be found in the English Clearpond database.

The L1-German vocabulary consists of 14,546 words; the C1-English vocabulary contains 5387 words. The bilingual network resulted from a merging of the two vocabularies (also see Luef, 2025a).

Next, phonetic transcriptions of the German and English words were copied from the Clearpond database in the form of CP-SAMPA transcriptions. The German transcriptions were manually checked and some were corrected. The transcriptions were then altered in various ways: dots between symbols were removed and transcriptions consisting of multiple symbols were replaced with single symbols (e.g., "E3" was replaced with "e"). Homophonous word forms were merged (e.g., German "bis-Biss"/ *Engl. until-bite*; English "see-sea"). Then, the transcribed German and English words were entered into an *Oracle 12c Big-Data-Lite* database (Bryla, 2015) and the function *edit_distance* of the package "utl_match" was used to compare all word forms to one another and identify one-segment phonological neighbors that differ by a single segment through either addition, deletion, or substitution (Landauer & Streeter, 1973). Table 1 shows an example result from the Oracle database. (See Table 2.)

Separate analyses were conducted for the German vocabulary, the English vocabulary, and the bilingual German-English vocabulary, resulting in lists of phonological neighbors in the three vocabularies.

Phonological networks were created for each of the three vocabularies, with the entirely of all words of a vocabulary being entered and all one-segment neighbors being linked to one another. The R package "igraph" (Csardi & Nepusz, 2006) and the network software "Gephi" (Bastian et al., 2009) were used for network statistics and visualizations.

3.2. Participants

Sixty-nine first-language users of German (identification of 53 as female, 11 as male, and 5 as non-binary; age M = 23.4 years, range 18–26) who are majoring in English Studies at a German university were recruited and gave written consent to participate in a vocabulary questionnaire and an auditory lexical decision task. Second language proficiency can be estimated based on the 'Common European Framework of Reference', which proposes six proficiency levels, starting with

Table 1
String distances (edit distances) between the word "a" and other words in the L2-English lexicon. Distance measurements are based on SAMPA transcriptions of the original phonetic transcriptions (IPA). String distances of "1" are treated as phonological neighbors.

word	*IPA*	*CP-SAMPA*	*tested against*	*IPA*	*CP-SAMPA*	*String distance*
a	eɪ	eI	able	eɪbl	eIbl	2
a	eɪ	eI	about	əbaʊt	5baUt	5
a	eɪ	eI	above	əbʌv	5bVv	4
a	eɪ	eI	ache	eɪk	eIk	1
a	eɪ	eI	add	æd	1d	2
a	eɪ	eI	against	əgenst	5gEnst	6
a	eɪ	eI	aim	em	eIm	1

Table 2
Target words and neighborhood frequency statistics, including German, English, and pseudo neighbors in both languages.

	GERMAN		ENGLISH	
Target word	*Sum of all frequencies within a neighborhood*	*Standard deviation*	*Sum of all frequencies within a neighborhood*	*Standard deviation*
Belt	1391.3	249.4	664	164.4
Bike	1698.9	568.9	4821.7	1593.5
Climb	119.3	29.7	96.6	32.4
Clue	84.3	14.1	158.6	47.1
Cost	28.3	12.2	391	129.4
Dawn	12,402.4	2104.1	498.4	276.2
Dime	81.5	18.4	1989.6	1121.9
Down	2750.9	1337.4	321.8	114.9
East	352.4	164.9	466.4	130.7
Egg	21,498.6	6546.5	2357.1	693.3
False	182.5	122.1	125.7	58.3
Field	1139.9	455.7	186.5	48.8
File	1389.1	255.3	1536.8	210.3
Floor	14.8	3.3	3591.5	2059.7
Fly	203.8	59.1	221.1	48.1
Foot	37.7	10.7	5004.4	1632.2
Fuss	100.6	28.5	322	115.2
Guest	972.8	221.2	5810.7	1664
Guilt	833.8	211.6	168	12.9
Hall	424.9	100.5	2026	307
Help	161.3	28.6	513.1	260.3
Hint	1531.1	182.9	309.8	132.1
Hire	214.4	25.1	500.7	145.6
Hour_our	12,332.6	1819.5	3876.7	2228.3
How	826.9	100.4	4278.7	1325.5
Kind	1903.7	484.5	1318.8	415.6
Left	122	57.2	2460	1385
Lost	162.4	25.9	1095.5	289.9
Loud	476	75.6	4008.7	1452
Melt	1156.5	266.7	128.6	56.4
Mess	14,941.9	5611.9	3053.5	757.7
Mile	4423.8	628.4	8030	2333.9
Mint	6821.3	2077.9	494.4	175.5
Mouth	83.1	25.5	83.6	32.1
Now	2269.9	495.9	9088.6	2599.3
Ought	1800	354.4	29,609	6719.9
Out	11,970.4	1440.6	1790.2	359.4
Owl	11,045.5	1785.6	5020.1	1264.9
Piece_peace	412.8	80.5	152.3	40.9
Pile	1097.9	296.4	488.5	117.2
Shift	252.9	56.1	98.6	21.5
Shoot	3093.6	1040.1	658.7	105.9
Shout	371.4	84.5	3951.7	1918.4
Talk	946.7	221.8	239.1	118.1
Time	235.8	63.7	187.6	23.2
Town	46.1	8.9	1544.6	660.4
Tube	1306.1	506.9	8427	3737.9
Vet	5534	1101.8	7837.1	1590.7
Zoo	44,648.4	9430.8	59,371.1	15,064.6

the beginner levels A1 and A2, followed by intermediate levels B1 and B2, and the advanced levels C1 and C2 (see Council of Europe, 2018). All participants self-reported English proficiency at level C1 (advanced), which was the average proficiency required for admission to the university study program. None of them had any hearing or language disorders. Aside from German as their first and English as their second languages, if participants knew a third language, they only had basic knowledge of it. They received course credits for their participation. Data were collected between April and December 2024. The study was approved by the ethics review board of Charles University (reference number UKFF/46874/2023).

3.3. Vocabulary questionnaire

50 English words typically known by L2-English learners at lower and intermediate proficiency levels (A1, A2, B1, B2) were selected as stimuli (see Appendix Table A for an overview of the target words and their neighbors). They were controlled for a variety of factors (see section 3.6) but differed systematically in terms of their German neighborhood frequencies. The constraints that were imposed by the study design prevented more words from being eligible for testing. Requirements included target words to be of lower lexical frequency as such words are known to amplify neighborhood effects (Andrews, 1992; Luef, 2025a; Sears et al., 1995), while at the same time having at least 50 % German neighbors in the phonological neighborhood. As English and German neighborhood densities and frequencies are typically correlated (densities: $r = 0.5$; frequencies: $r = 0.7$), high-density/frequency English neighborhoods are characterized by high-density/frequency cross-language German neighborhoods. This meant that some combinations of low-frequency English target plus medium- to higher-frequent German neighbors were rarer instances to be found in the bilingual lexicon. This reduced the number of available stimuli. In addition, words from specific network density regions were chosen as targets, excluding other potential English targets. Please see section 3.6. for a description of each controlled factor.

Knowledge of all involved German neighboring words was expected based on the first-language German proficiency of the participants. All participants were tested on their knowledge of the English words involved in the experiment, both target words and their phonological neighbors. In an online survey, participants were asked to rate their familiarity with the words, i.e., whether they knew a word (*answer options*: "I know the word", "I have never heard the word", "I am not sure"). The familiarity ratings were obtained from visually presented words. Words were removed from the data set when more than 30 % of participants stated that they did not know a word or were unsure. This was the case with one word, *fowl*, a neighbor of the target words *owl* and *file*. *Fowl* was taken out of neighborhood density and frequency calculations. The other target and neighboring words were well known by the participants.

80 % of the participants completed the experiment shortly before they took the vocabulary questionnaire, and in the large majority of cases both tasks were completed within one hour. It may have been possible that the 20 % who took the vocabulary questionnaire before the experiment were primed by the words they were exposed to in the questionnaire.

3.4. Pseudo-neighbors

Second language perception may be influenced by the first language of listeners, leading to confusability of segmental contrasts on the lexical level (Bohn & Flege, 1992; Rocca et al., 2025). A well-researched aspect of this is the English [æ] - [ɛ] contrast that may be difficult to perceive for many German learners of English (Llompart, 2021; Llompart & Reinisch, 2020). The difficulty in distinguishing these vowels leads to additional phonological neighbors that are based on erroneous perception. For instance, the English words "beg" [bɛg] and "bag" [bæg] may sound identical to German listeners at beginning but also intermediate and advanced levels (see Llompart, 2021), which may result in different perceptual phonological neighborhoods as compared to native speakers of English. Taking these perceptual accents into account can lead to a better estimation of a phonological neighborhood in second language learners (Amengual, 2016; Darcy et al., 2013; Weber & Cutler, 2004).

This study took into account the following phonological features that were assumed to skew German L2-English learners' perception at proficiency level C1 (see Hickey, 2019): (a) the perception of [æ] as [ɛ], (b) voicing in word-initial sibilants (e.g., [zi:] for English "sea"), and (c) devoicing in word-final obstruents (e.g., [bɪk] for English "big"). Five target words were affected: *egg, field, kind, loud,* and *tube*. Using the phonetic transcriptions of the German-accented words [ɛk, fiːlt, kaɪnt, laʊt, tuːp] phonological neighbors in German and English were searched in the phonological networks of the languages and a total of 22 words were added to their respective neighborhoods. The [ɛk] neighborhood received additional German "Ecke" (Engl. *corner*), German "Leck" (Engl. *leak*), Engl. "back", "pack", "lack", sack", "bag". The [fiːlt] neighborhood received the additional German word "Feld" (Engl. *field*) and the English word "fault". The [kaɪnt] neighborhood received additional German "Feind" (Engl. *enemy*), German "Kind" (Engl. *child*), and English "pint". The [laʊt] neighborhood received additional German "Land" (Engl. *land*), "Last" (Engl. *load*), German "Haut" (Engl. *skin*), and English "route", "shout", "out", and "doubt". The [tuːp] neighborhood received additional German "taub" (Engl. *deaf*), German "Tipp" (Engl. *tip*), and English "soup". Phonological similarities between the pseudo-neighbors and their neighborhoods were calculated and included in the neighborhood metrics. The frequencies of the neighborhoods were updated to include the individual frequencies of those pseudo-neighbors in the German and English Clearpond databases.

3.5. Lexical decision experiment

An auditory lexical decision task was created with PsychoPy 2023.2.3 (Peirce et al., 2019). The presentation of stimulus words was randomized, and accuracy in word judgments as well as reaction time measurements to correct judgments were extracted for analysis. Audio stimuli of the 50 real words and 50 pseudo-words (or "non-words") were obtained from the MALD database (Tucker et al., 2019), with all words being spoken by an American male speaker. His accent can be described as Midland or Western United States, possibly Colorado or California. His speech showed a clear cot-*caught* distinction and no traces of Northern Cities Vowel Shift or Southern phonetic features (as evaluated by ChatGPT based on a sample of 5 recordings).

The pseudo-words differed from real English or German words by one segment. Words that could mistakenly be perceived as an accented English word by German learners of English were not selected as pseudo-words (e.g., /ʧis/ which could be perceived as an acceptable pronunciation of "cheese" by German listeners).

The experiment was made available online on the Pavlovia platform via a link that was given to the participants. Each participant was tested individually at their own computers; they were instructed to use headphones. Trials started with the presentation of a small cross on the screen for 500 ms. After that, target words and pseudo-words appeared in successive, randomized order and only once before participants had to decide (as quickly as possible) whether a word they heard is a real English word or a pseudo-word by pressing either "a" or "k" on their keyboards. Response times were measured from the onset of the stimulus to the onset of the key press response. Each new item was presented 500 ms. after the previous response. Inter-trial intervals were not fixed but participants were given infinite time to respond to a target word before a trial ended. There was no planned pause (or timeout) during the experiment.

Prior to the experiment, participants were given seven practice trials to familiarize themselves with the procedure and to adjust the volume of the auditory stimuli. The practice trials were excluded from the analyses. The experiment lasted about 10 min.

3.6. Variables

3.6.1. English neighborhood frequency

The overall frequency of the English phonological neighborhood, calculated as the sum of the individual frequencies of all neighboring words within the target word neighborhood was based on word frequencies obtained from the Clearpond (English) database (Marian et al., 2012). English neighborhood frequency values ranged between 84 and 59,371 per million.

3.6.2. German neighborhood frequency

Each English target word had a minimum of 50 % German neighbors in the bilingual phonological neighborhood. The overall frequency of the German phonological neighborhood of an English target word was calculated as the sum of the individual frequencies of all German neighbors, based on the Clearpond database for German. Neighborhood frequencies ranged between 15 and 44,648 per million. A wide distribution of German neighborhood frequencies was a criterion for English target word selection.

The following lexical characteristics were considered for each target word.

3.6.3. Length of words

Monosyllabic words with 2 to 4 segments served as stimuli. Word length was determined by phonetically transcribing the target words (with *ToPhonetics*) and counting segment length with the Excel function *LEN()*.

3.6.4. English lexical frequency rate

Frequency rates of the target words were obtained from the Clearpond database for English. All words ranged in the lower frequency spectrum of 3–3865 per million. There are indications in previous studies that neighborhood effects are amplified in low-density/ low-frequency target words (Andrews, 1989, 1992; Forster & Shen, 1996; Luef, 2025a; Sears et al., 1995), leading to better detection of potentially milder neighborhood effects. In the present study, the target words were never the highest-frequency words within their neighborhoods. This allowed better testing of the effect of the neighbors on target recognition.

3.6.5. Phonotactic probability

Biphone probabilities of the English target words were calculated with the *Phonotactic Probability Calculator* (Vitevitch & Luce, 2004). Biphone probability values reflect the sum of all biphone probabilities within a given word. Probabilities of target words ranged between 0.0001 and 0.0422.

3.6.6. Presence of cognates

Being typologically close, English and German share many cognate word forms. In the present data, it was coded whether a cross-language phonological neighborhood contained any similar word forms with similar meanings in modern English and German (i.e., excluding historical cognates that have become phonologically non-transparent). Eight target words each had one German cognate in their neighborhood, in all cases translation terms with near identical meanings (i.e., *east* – Germ. "Ost", *guest* – Germ. "Gast", *loud* – Germ. "laut", *mile* – Germ. "Meile", *mouth* – Germ. "Maul", *out* – Germ. "aus", *shift* – Germ. "Schicht", *tube* – German "Tube"), including one pseudo neighbor: *field* – Germ. "Feld".

3.6.7. Phonological neighborhood density

What is referred to as "degree" in phonological networks is the one-segment distance between phonological word forms ("Levenshtein distance", see Levenshtein, 1966), which is the basis of neighborhood creation. Neighborhood density calculations were obtained from the C1-English network. Only target words with sparse phonological neighborhoods of less than 10 neighbors in English were selected. The target words had between 2 and 9 English neighbors. The target words had between 2 and 18 German neighbors (the latter being quite dense neighborhoods in the German language).

3.6.8. English weighted degree

The network term "weighted degree" refers to the strength of a link between two nodes. In the present study, phonological similarities between target words and their neighbors (including pseudo-neighbors) were calculated with the ALINE algorithm, computed with the "alineR" package in R (Downey et al., 2008). In the present case, the algorithm compared phonological features of the one segment that distinguished the phonological neighbors in English, including for instance manner, place, aspiration, nasality, and roundness (see Downey et al., 2017, for details). The ALINE distance score ranges between 0 (=perfect agreement) and 1 (=maximal phonological distance). It was converted to a similarity score by reverse scoring and multiplying the value by 100 (e.g., an ALINE score of 0.2 was converted to 80). This resulted in percentage-based phonological similarity scores that lead to more intuitive link strengths in a network (see Table 3). English weighted degree represented the average of all phonological similarities between a target word and its English neighbors. It ranged between 58 and 90.

3.6.9. German weighted degree

ALINE scores were calculated between the English target words and their German phonological neighbors (and pseudo-neighbors), identical to the computations of English weighted degree. German weighted degree represented the average of all phonological similarities between a target word and its German neighbors. It ranged between 47 and 92.

Weighted degrees and neighborhood frequencies in English showed a substantial negative correlation ($r = -0.55$), which may indicate that higher frequency words are less phonologically similar to one another. The relationship between German neighborhood frequency and weighted degree was less pronounced ($r = -0.32$, English), which may reflect the fact that lexical frequencies rates and phonological similarity are less tightly bound. Essentially, these correlative relationships may be artifacts of segmental and phonotactic frequencies (and probabilities) in the languages.

3.6.10. Clustering in the bilingual neighborhood

The clustering coefficient (""CC") is a network statistic that measures the degree of interlinking of neighbors within a neighborhood (see Fig. 4). It measures how many neighbors of a target word are linked to one another. CC is based on the formula

$$CC = 2e_n / (k_n (k_n - 1))$$

which outputs values between 0 and 1, with the latter representing complete interlinking of all neighbors (Watts & Strogatz, 1998). In this study, only words with an intermediate CC between 0.2 and 0.6 in the bilingual German-English neighborhood were chosen as target words.

3.6.11. Network statistics

All target words resided in the giant component part of the English-German phonological networks, which is the largest cluster of interconnected nodes in a network (Siew & Vitevitch, 2016). A "network density" compound variable was constructed by averaging the following five (log-transformed) bilingual network statistics: degree, weighted degree, clustering coefficient, as well as eigenvector centrality, and closeness centrality. Eigenvector centrality takes into account the centralities of neighboring nodes and assigns the highest values to those words that have highly centralized neighbors (Bonacich, 2007). Through this, words with many neighbors that have themselves many neighbors can be identified. Such a structure is indicative of the density of a particular network area. Closeness centrality is a measure of how close each node is to all other nodes in a network when measuring the shortest distance (Salavati et al., 2019). It can be understood as the inverse of the average distance from a given node to all other nodes in a network. High values indicate that a word is close to numerous other words in a network, which is indicative of the density of the network part in which a word resides (Goldstein & Vitevitch, 2017; Vitevitch & Goldstein, 2014). High values in the aggregate of the five metrics indicate denser areas in the overall bilingual network.

Table 3
Phonological similarity scores calculated with the ALINE algorithm between the word "a" and three of its phonological neighbors.

word	*phonetic*	*neighbor*	*phonetic*	*alineR output*	*rescaled value*
a	eɪ	ache	eɪk	0.37	63
a	eɪ	age	eɪʤ	0.37	63
a	eɪ	air	eə	0.17	83

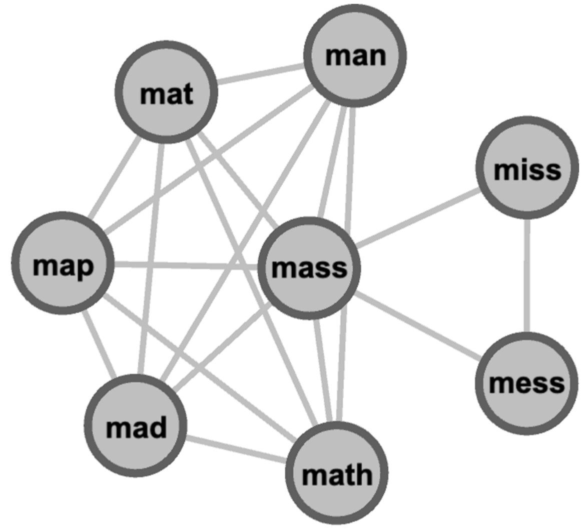

Fig. 4. Clustering in the "mass" neighborhood. The clustering coefficient of 0.52 indicates that a high number of phonological neighbors of "mass" are neighbors of one another, as indicated by the links.

Fig. 5 illustrates the relationship between the network statistics in a partial English phonological network where the densest region (indicated with darker nodes) can be identified using the five metrics outlined above. The highest-degree word (i.e., the one with the most phonological neighbors) is *grace*, followed by *great, grape, grade, grave,* and *gray*. These are also the words with the highest weighted degrees. The same words are also the ones with the highest CC in the network, as they are all linked to one another in their neighborhoods. The neighborhood around *grape* is also characterized by highest Eigenvector centrality, and many of its members show the highest closeness centrality values of the network (i.e., *trace, grace, race*). Conversely, the words *trial* and *trail* are characterized by lower values in degree, weighted degree, CC, closeness and eigenvector centralities in the network. A combination of these network statistics can inform about the density of a specific network region where a target word is located. All target words used in the lexical decision task stemmed from parts of the phonological network that are characterized by intermediate density, with logarithmic values of the compound density variable ranging between −0.13 and 0.37. Since this range is broad, the density variable was added as a control variable to the statistical models.

3.7. Statistical analysis

After experimental data collection, reaction time data was cleaned and sorted in various ways. First, responses below 200 ms were removed, as they indicate non-processing of the stimulus (Whelan, 2008). Reaction times per participant were z-scored and values exceeding +3 or − 3 were considered outliers and removed. Target words that elicited more than 30 % of judgment errors were deleted from the dataset. This affected two words, "owl" and "shout". In addition, one target word, *time*, had to be removed as the audio file turned out to be corrupted. The overall data removed amounted to 5.6 % of the raw data. A total of 47 words remained and were processed for further analysis. One spread sheet containing all responses ($N = 3161$) was compiled, in addition to one containing only correct responses ($N = 3058$).

A generalized linear mixed effects model (GLM) was run in R with the package *lme4* (Bates et al., 2014) to see whether the accuracy of word judgments (as real or non-words) was influenced by the frequency of the German neighborhood of a target word. As dependent variable the

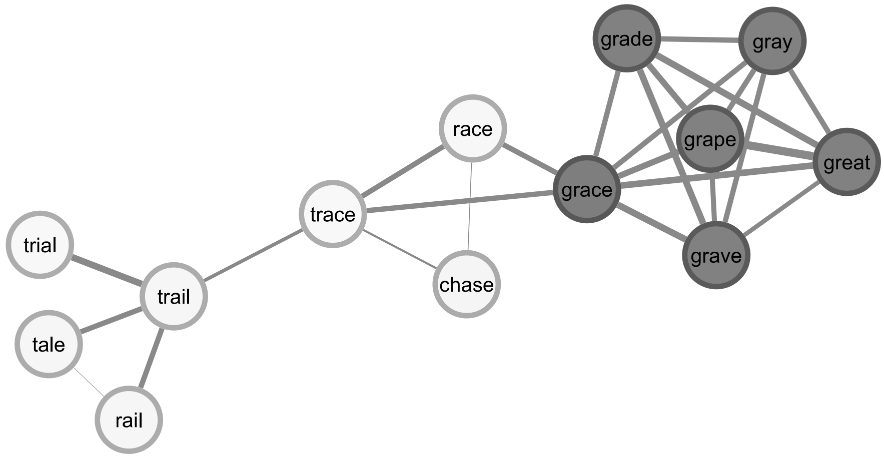

Fig. 5. A partial phonological network. The darker area indicates the densest network region in terms of degree, weighted degree, clustering coefficient, closeness centrality, and Eigenvector centrality.

binary outcome "correct/incorrect" was entered. The following fixed effects were included: an interaction variable of German neighborhood frequency and German weighted degree as the variable of interest, in addition to a number of control variables, including English neighborhood frequency interacted with English weighted degree, lexical frequency rates of target words, presence of cross-language cognate (yes/no), and density of the network part in which the target word resided. No correlations between fixed effects were detected. Random effects for target word and participant ID were specified, with random slopes for German and English neighborhood frequencies, as well as for lexical frequency rates of the target words. A binomial regression with "cloglog" links was specified in the GLM, as the data contained a larger number of correct than incorrect responses (only 3.3 % were incorrect). No convergence issues appeared during the computation.

As a next step, a linear mixed effects model (LME) was computed to investigate the influence of German neighborhood frequency on reaction times in milli-seconds to target words. The LME model only included correct responses of the participants. The LME was structured in an identical way to the GLM. For the LME model, degrees of freedom and significance values can be estimated via approximations, for which the Satterthwaite's method is commonly used. Functions for it were utilized in the R package *lmerTest* (Kuznetsova et al., 2017).

4. Results

As is typically the case in lexical decision tasks, responses to non-words were slower than responses to real words (average non-words = 2.39 s., SD = 1.54; average real words = 1.75 s., SD = 0.81), indicating faster processing of real words.

4.1. Accuracy of word judgments

Table 4 summarizes the results of the generalized linear mixed effects model that tested whether there was any difference in lexical characteristics of words that were accurately judged (e.g., real words being judged as real words) or incorrectly judged (e.g., a non-word judged as being a real word). The sample size of this accuracy model was 3161 responses. German neighbors were not shown to influence accuracy of word judgments (see Table 4). Results yielded only effects of target word frequency rate on the accuracy of the word judgments, where a significance of $p = 0.01$ indicates that the accuracy of word judgment increases together with lexical frequency rate of target words (i.e., 0.36 higher log odds of accurate judgment, see estimate in Table 4).

Correctly judged target words (i.e., real words as real words) were generally characterized by higher lexical frequency rates than those words that were judged incorrectly.

Table 4
Generalized linear mixed effects model estimates for fixed and random effects. Judgment accuracy model.

Variable	*Variance*	*Estimate*	*SD*	*SE*	*z*	*p*
Random effects						
Participant						
German neighborhood frequency	9.264e-03		0.0962479			
English neighborhood frequency	1.411e-02		0.1187986			
Lexical frequency rate	4.634e-01		0.6807021			
Word						
German neighborhood frequency	1.333e-01		0.3651588			
English neighborhood frequency	1.277e-02		0.1129883			
Lexical frequency rate	2.201e-05		0.0046910			
Fixed effects						
Intercept		−19.36		20.37	−0.95	0.34
German neighborhood frequency		3.24		4.55	0.71	0.48
German weighted degree		1.93		7.65	0.25	0.8
English neighborhood frequency		2.54		4.46	0.57	0.57
English weighted degree		8.88		8.46	1.05	0.29
Target lexical frequency rate		0.36		0.15	2.45	0.014 *
Network density		−0.65		0.75	−0.87	0.39
Cognate presence		0.26		0.19	1.41	0.16
German neighborh. Frequ. & German weighted degree (interaction)		−1.75		2.4	−0.73	0.47
English neighborh. Frequ. & English weighted degree (interaction)		−1.27		2.38	−0.53	0.59

* $p < 0.05$.

4.2. Reaction times

Testing reaction times to target words, the linear mixed effect model results are presented in Table 5. Incorrect responses were removed from the sample, resulting in a sample size of 3057 responses for the reaction times model. As indicated in Table 5, reaction times were influenced by German neighborhood frequency, German weighted degree, as well as the interaction between the two. The absence of any effects of English neighborhood frequency will be discussed below.

The interacted variable of German neighborhood frequency and German weighted degree was associated with response latencies to target words. The positive estimate indicates that more frequent and phonologically similar German neighbors caused a delay in recognition of an English target words. Inspecting the interaction more closely, differences emerge in terms of the effect of phonological similarity and frequency (see Fig. 6).

German weighted degree is the moderating variable that impacts the relationship between reaction times and German neighborhood frequency. Neighborhoods with phonological similarity values of one standard deviation above the mean (i.e., +1 SD) show a strong association between higher neighborhood frequency and longer response latencies. This means that frequent German neighbors led to longer reaction times in cases where phonological similarity was high. Phonological similarities values below the mean (i.e., −1 SD) show the reverse effect of shorter response latencies to target words with higher frequency neighborhoods, implying that phonologically dissimilar German neighbors elicited shorter response times in high-frequency German neighborhoods. Hence, the observed cross-language neighborhood effect was mediated by phonological similarity of the cross-language neighbors.

Table 5
Linear mixed effects model estimates for fixed and random effects. Reaction time model.

Variable	*Variance*	*Estimate*	*SD*	*SE*	*p*
Random effects					
Participant					
German neighborhood frequency	8.898e-07		0.0009433		
English neighborhood frequency	3.669e-07		0.0006057		
Lexical frequency rate	1.181e-06		0.0010868		
Word					
German neighborhood frequency	2.343e-05		0.0048400		
English neighborhood frequency	5.636e-05		0.0075072		
Lexical frequency rate	1.929e-04		0.0138890		
Fixed effects					
Intercept		2.42		0.84	0.01 *
German neighborhood frequency		−0.41		0.13	0.005 **
German weighted degree		−0.74		0.26	0.013*
English neighborhood frequency		−0.12		0.19	0.54
English weighted degree		−0.42		0.38	0.29
Target lexical frequency rate		−0.01		0.004	0.08
Network density		−0.03		0.036	0.47
Cognate presence		0.005		0.01	0.47
German neighborh. Frequ. & German weighted degree (interacted)		0.22		0.07	0.0056 **
English neighborh. Frequ. & English weighted degree (interacted)		0.06		0.11	0.55

* $p < 0.05$.
** $p < 0.01$.

5. Discussion

5.1. Main findings

This study investigated the effect of neighborhood frequency in bilingual phonological neighborhoods of German learners of English as a second language. Results demonstrate that higher lexical frequencies of cross-language neighbors (i.e., German neighbors of English target words), especially in connection with high phonological similarity, delay reaction times to English target words. This finding underscores the influence of a first language on a second, learned language and provides evidence for a cross-language frequency effect on the lexical level.

5.2. Implications

Support for an integrated bilingual word form lexicon, where activation spreads across languages, primarily stems from neighborhood density investigations, taking into account the number of phonological neighbors a target word has (e.g., Blumenfeld & Marian, 2007; Canseco-Gonzalez et al., 2010; Ju & Luce, 2004; Lagrou et al., 2011; Luef, 2025a; Marian & Spivey, 2003; Shook & Marian, 2012; Weber & Cutler, 2004). This study is the first to report on neighborhood frequency effects in a cross-linguistic context. Frequency effects seem to heighten competition in neighborhoods where word forms from multiple languages share activation. Especially in late bilingualism, where a dominant first language often overshadows a second language, the L1 word forms exert strong influence in a neighborhood (Spivey & Marian, 1990; Weber & Cutler, 2004; Wen & van Heuven, 2017). It is likely that first language lexical frequencies are more deeply entrenched in speakers' mental lexica and therefore have a stronger impact than second language lexical frequencies (Diependaele et al., 2013). Cross-linguistic frequency effects change the trajectory of lexical activation spreading, which leads to different predictions regarding word recognition. This creates an imperative to consider frequency effects in studies of the bilingual lexicon, analogous to what has been proposed by Luce and Pisoni (1998) for monolingual neighborhoods.

Previous research has shown that smaller vocabularies typically exhibit larger frequency effects (Brysbaert, Lagrou, & Stevens, 2017), a finding of relevance for second languages (Cop et al., 2015). According to the lexical entrenchment hypothesis, less exposure to (and proficiency in) a language leads to more pronounced frequency effects (Brysbaert, Lagrou, & Stevens, 2017). A smaller number of words being used repeatedly – as is commonly the case with second languages – leads to deeper cognitive embedding of these words and amplifies frequency effects. It is notable that no L2 neighborhood effects were observed in the present study. There are two explanations that seem likely in the present case. For one, neighborhood effects may be dominated by the first language but not there yet for L2 neighborhoods. In this context the question arises how advanced an L2 learner must be for those L2 neighborhood effects to arise. This study involved L2 learners at a quite advanced proficiency level (CEFR-C1), so it would be expected that neighborhood effects should play some role in lexical processing. In fact, L2 learners at this proficiency level were previously found to show neighborhood density effects (Luef, 2025a). An alternative explanation for the absence of English neighborhood effects could be the specific limitations imposed on target word selection. Stimuli were chosen that

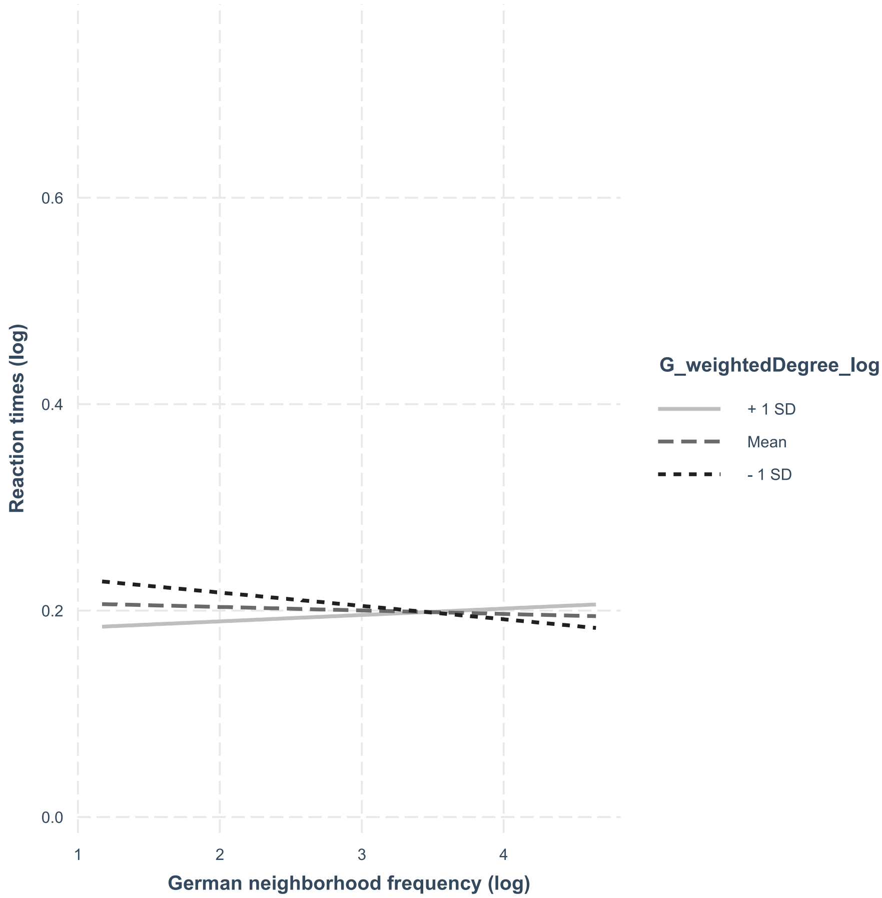

Fig. 6. The interaction between German neighborhood frequency and weighted degree (=phonological similarity) is such that high-frequency neighborhoods coupled with close phonological similarity lead to longer reaction times.

were quite homogeneous in terms of their English lexical characteristics. This particularly concerns the constraint on target lexical frequency (i.e., in the low frequency range) and L2 neighborhood density (i.e., <10 English neighbors). Since the English words fell within a slim range of a variety of controlled variables, neighborhood effects may have been suppressed in this sample.

A finding of relevance for late bilingual lexical neighborhoods is the age-of-acquisition effect. The age at which a word is learned, and thus the length it has been present in a mental lexicon, determines a large portion of its activation (A. W. Ellis & Lambon Ralph, 2000; Elsherif et al., 2023). Words learned at a young age are thought to be more deeply ingrained in linguistic cognition – due to repetition effects – and they incorporate more of the overall lexical activation (Karimi & Diaz, 2020). This means that earlier learned words – especially if numerous – impede retrieval of later learned words, a finding of obvious relevance to second languages processing. Age-of-acquisition of a word is highly correlated with lexical frequency, and higher frequency words are the ones that are learned first in second language learning (Luef, 2023). This relationship highlights the importance of neighborhood frequency in bilingual phonological neighborhoods.

The use of phonological network science for spoken word recognition has proven invaluable for psycholinguistic study (e.g., Chan & Vitevitch, 2009; Goldstein & Vitevitch, 2017; Luef, 2025a; Siew & Vitevitch, 2016). Network parts are characterized by different degrees of connectivity (or density) and a number of network statistics have been developed that can mathematically place a word form within a network. In this study, target words (and their neighbors) were selected from mid-density regions of the phonological network, which are network regions where a large number of words can be found in a lexicon (Luef, 2025b).

5.3. *Limitations*

This study has a number of limitations. The corpus data underlying the analyses may underestimate the vocabulary sizes in both L1-German and L2-English. The lexical contents of corpora are dependent on the tasks which elicit the speech (see Gráf, 2017, for a discussion). Of concern may be the translational nature of the German data, which stems from English subtitles and may not represent a completely naturalistic German lexicon. An additional caveat concerns the question of phonological pseudo-neighbors, a critical consideration in studies of second language lexical processing (see, e.g., Rocca et al., 2025). Even though the present study included pseudo-neighbors of the target words, the network centralities measures were not based on extended pseudo-neighborhoods (i.e., pseudo-neighbors of pseudo-neighbors). Incorporating all possible pseudo-neighbors in an entire L2- lexicon would lead to a significant expansion of the vocabulary. Furthermore, it would introduce a substantial amount of bias since pseudo-neighbors are based on presumed phonological discrepancies that may not apply to all L2 learners. Modeling a phonological network after canonical English word forms is certainly a simplification of the L2 phonological reality but could be seen as more generalizable. Stress, pitch, and rhythmic patterns are major issues for German learners of English (at advanced proficiency stages) but pseudo-lexica based on those features would add immense complexity to a phonological network. Such an analysis was beyond the scope of the present study.

5.4. *Future directions*

An intriguing research question for a future study concerns an exploration of near versus distant phonological neighbors and their frequencies in the entire bilingual word form network. Based on the theoretical framework of attractor dynamics (e.g., Mirman & Magnuson, 2008), 'attractor regions' could be computed within the entire phonological network and their relevance for lexical processes could be tested. In attractor models of linguistic cognition, lexical memory is pulled toward stable states into which the brain's activity naturally settles (=attractors). Strong attractors correspond to words with many closely related words that pull the system toward them; weak attractors are words with more distant neighbors (Mirman, 2011). This dynamic has crucial effects on lexical competition. With the use of assortativity metrics in (weighted) networks (Leung & Chau, 2007), attractor dynamics could be identified. Charting the distribution of strong and weak attractors within a (mono- or bilingual) phonological network can help find areas where lexical processing is more burdensome or facilitated. A methodological alternative could be the detection of network communities (Chern et al., 2025; Siew, 2013) and their organizational structure in terms of strong and weak attractor constituents. Cross-language neighbors, being phonologically more distant in many cases (Luef, 2025a), potentially influence the attractor dynamics present in a bilingual network and render it different from the monolingual networks of individual languages.

6. Conclusion

In sum, this study presents evidence for a neighborhood frequency effect in bilingual German-English phonological neighborhoods. The finding shows that neighborhood frequency can be a factor in bilingual cognition and the described results can contribute to the discussion of lexical competition in second language processing.

CRediT authorship contribution statement

Eva Maria Luef: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

"I have nothing to declare".

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Appendix A

Table A
Target words with German translations; phonological neighbors with German/English translations, phonetic transcriptions, and cognate status of each neighbor. The last column lists the pseudo words used in the experiment.

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
belt	English	bell	bɛl	Glocke		rowf /roʊf/
Gürtel		melt	mɛlt	schmelzen		shraest /ʃræst/
		best	bɛst	beste/r		kayiys /kaɪz/
		bet	bɛt	Wette		maarm /marm/
		built	bɪlt	gebaut		faarlz /fɑrls/
	German	Geld	gɛlt	money		prihd /prɪd/
		bald	balt	soon		kaadz /kɑdz/
		Feld	fɛlt	field		mawnsh /maʊnʃ/
		Held	hɛlt	hero		gahvd /gɑvd/
		Welt	vɛlt	world		iynt /int/
bike	English	like	laɪk	mögen, wie		soihn /soɪn/
Fahrrad		buyer	baɪər	Käufer		ruwk /ruk/
		bite	baɪt	beißen		dahr /dɑr/
		bake	beɪk	backen		teych /teɪt͡ʃ/
		brick	brɪk	Ziegel		flowk /floʊk/
		by_bye	baɪ	von, bei		puwriy /puri/
	German	Beil	baɪl	hatchet		lehmd /lɛmd/
		Bein	baɪn	leg		blaem /blæm/
		Bank	baŋk	bench, bank		ihmeyn /ɪmeɪn/
		Balg	balk	bellows		luwngk /lʊŋk/
		Blick	blɪk	view		bawks /baʊks/
		Teig	taɪk	dough		hhaadz /hɑdz/
		bei	baɪ	at, by		awnd /aʊnd/
climb	English	claim	kleɪm	beanspruchen		buwkt /bʊkt/
klettern		crime	kraɪm	Verbrechen		paydiy /paɪdi/
	German	Leim	laɪm	glue		leyts /leɪts/
		Keim	kaɪm	germ, seed		sawch /soʊʃ/
		Schleim	ʃlaɪm	slime		prayl /praɪl/
		Klamm	klam	clamp		ihlbaxt /ɪlbæt/
		Kleid	klaɪt	dress		skaamp /skɑmp/
		klein	klaɪn	small		kaez /kæz/
clue	English	crew	kru	Mannschaft		baazh /bɑz/
Hinweis		flu	flu	Grippe		gihch /gɪt͡ʃ/
		blue	blu	blau		mahraen /maræn/

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
	German	Kuh_Coup	ku	cow, coup		praa /pra/
		Klub	klup	club		aengk /æŋk/
		klug	kluk	smart		vowvz /voʊvz/
		Klo	klo	toilet		prowk /proʊk/
		Klee	kle	clover		ihnsiy /ɪnsi/
cost	English	caught	kɑt	gefangen		showk /ʃoʊk/
Kosten		lost	lɔst	verloren		feybz /feɪbz/
		cast	kæst	gießen, Besetzung		reylt /reɪlt/
	German	Ost	ɔst	East		puhnd /pʊnd/
		Rost	ʁɔst	rust		yihliy /jɪli/
		Post	pɔst	post, mail		baeft /bæft/
dawn	English	done	dʌn	fertig, gemacht		hhayng /haɪŋ/
Dämmerung		yawn	jɔn	gähnen		hhuwdz /hudz/
		lawn	lɔn	Rasen		tayth /taɪθ/
	German	von	fɔn	from, by		baemz /bæmz/
		doch	dɔx	but		plahb /plʌb/
		Dorn	dɔɐn	thorn		
		Donner	dɔnnɐ	thunder		
		Dock	dɔk	dock		
		dann	dan	then		
		dünn	dyn	thin		
		denn	dɛn	because		
dime	English	dive	daɪv	tauchen		
cent		gym	ʤɪm	Fitnessstudio		
		time	taɪm	Zeit		
	German	daheim	dahaɪm	at home		
		Damm	dam	dam		
		Darm	dam	colon		
		Keim	kaɪm	germ, seed		
		heim	haɪm	home		
		Leim	laɪm	glue		
		Reim	ʁaɪm	rhyme		
down	English	doubt	daʊt	Zweifel		
unten		drown	draʊn	ertrinken		
		noun	naʊn	Nomen		
		town	taʊn	Stadt		
	German	Faun	faʊn	faun		
		dann	dan	then		
		dauern	daʊɐn	to last		
		Dauer	daʊɐ	duration		
east	English	feast	fist	schlemmen		
Ost/en		eat	it	essen		
		least	list	wenigsten, mindestens		
	German	erst	ɛɐst	first		
		Ost	ɔst	East	yes	
		Biest	bist	beast		
		Ast	ast	branch		
egg	English	leg	lɛg	Bein		
Ei		air_heir	ɛr	Luft, Erbe		
		beg	bɛg	betteln		
	German	es	ɛs	it		
		er	ɛɐ	he		
		eng	ɛŋ	narrow		
	Pseudo neighbors	Ecke (Germ.)	ɛkə	corner		
		Leck (Germ.)	lɛk	leak		
		back (Engl.)	bɛk	zurück		
		pack (Engl.)	pɛk	packen		
		lack (Engl.)	lɛk	fehlen, Mangel		
		sack (Engl.)	sɛk	Sack		
		bag (Engl.)	bɛk	Tasche		
false	English	Fox	fɑks	Fuchs		
falsch		fault	fɔlt	Fehler		
	German	Fels	fɛls	rock		
		falls	fals	if		
feast	English	first	fɜrst	zuerst		
Festmahl		East	ist	Osten		
		least	list	wenigsten, mindestens		
		feet	fit	Füße		
	German	First	fɪɐst	roof ridge		
		fest	fɛst	party, tight		
		Biest	bist	beast		
		fast	fast	almost		
		fies	fis	nasty		
field	English	shield	ʃild	Schild		
Feld		field	fid	Feld		
		yield	jild	Ertrag		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
	German	viel	fil	many		
		Fels	fɛls	rock		
		Fehler	felɐ	error		
	Pseudo neighbors	fault (Engl.)	fɔlt	Fehler		
		Feld (Germ.)	fɛlt	field	yes	
file	English	while	waɪl	während		
Datei		pile	paɪl	Stapel		
		mile	maɪl	Meile		
		fail	feɪl	scheitern		
		five	faɪv	fünf		
		fight	faɪt	Kampf		
		fill	fɪl	füllen		
		fine	faɪn	fein		
	German	geil	gaɪl	cool, good		
		heil	haɪl	intact, healed		
		Pfeil	pfaɪl	arrow		
		Teil	taɪl	part		
		Seil	zaɪl	rope		
		Fall	fal	incidence		
		Keil	kaɪl	wedge		
		Weil	vaɪl	because		
		Beil	baɪl	hatchet		
		fein	faɪn	delicate		
		Feier	faɪɐ	party		
floor	English	flow	floʊ	fließen		
Boden		flair	flɛr	Flair		
		for_four	fɔr	für, vier		
	German	Floß	flos	raft		
		Flop	flop	flop		
		Floh	flo	flea		
fly	English	lie	laɪ	Lüge		
fliegen		flight	flaɪt	Flug		
		fry	fraɪ	braten		
		ally	ælaɪ	Verbündete/r		
	German	Fleiß	flaɪs	diligence		
		Fleisch	flaɪʃ	flesh, meat		
		frei	fʁaɪ	free		
		Blei	blaɪ	lead (metal)		
		flach	flax	flat		
foot	English	out	aʊt	aus, raus		
Fuß		feet	fit	Füße		
		full	fʊl	voll		
		fat	fæt	fett		
		put	pʊt	setzen, stellen, legen		
	German	Futter	fʊtɐ	food		
		futsch	fʊtʃ	gone		
		fett	fɛt	fat		
		Schutt	ʃʊt	debris		
		Fund	fʊnt	discovery		
fuss	English	fun	fʌn	Spaß		
Aufregung		thus	ðʌs	also		
		bus	bʌs	Bus		
	German	fies	fis	nasty		
		Fass	fast	barrel		
		Fuß	fus	foot		
guest	English	West	wɛst	Westen		
Gast		best	bɛst	beste/r		
		rest	rɛst	Rest		
		guess	gɛs	Schätzung		
		get	gɛt	bekommen		
		nest	nɛst	Nest		
		test	tɛst	Test		
	German	Rest	ʁɛst	rest		
		fest	fɛst	party, tight		
		Gast	gast	guest	yes	
		Geld	gɛlt	money		
		Nest	nɛst	nest		
		Pest	pɛst	pest		
		Test	tɛst	test		
guilt	English	built	bɪlt	gebaut		
Schuld		gift	gɪft	Geschenk		
		guilty	gɪlti	schuldig		
	German	wild	wɪlt	wild		
		Schild	ʃɪlt	sign		
		mild	mɪlt	mild		
		Geld	gɛlt	money		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
		Gicht	gɪxt	gout		
		Bild	bɪlt	picture		
		Gift	gɪft	poison		
		Gold	gɔlt	gold		
hall	English	hill	hɪl	Hügel		
Flur, Saal		heal	hil	heilen		
		hell	hɛl	Hölle		
		ball	bɔl	Ball		
		call	kɔl	Ruf		
		ally	ɔl	Verbündete/r		
		wall	wɔl	Wand		
		hold	hoʊld	halten		
	German	Hall	hal	Echo		
		Hop	hɔp	hop		
		toll	tɔl	great		
		hohl	hol	hollow		
		voll	fɔl	full		
		Heu	hɔɪ	hay		
		hell	hɛl	bright		
help	English	health	hɛlθ	Gesundheit		
Hilfe		hell	hɛl	Hölle		
		helper	hɛlpər	Helfer		
	German	herb	hɛɐp	bitter		
		Helm	hɛlm	helmet		
		halb	halp	half		
		Gelb	gɛlp	yellow		
		hell	hɛl	light		
		Held	hɛlt	hero		
hint	English	hit	hɪt	Treffer, Schlag		
Hinweis		mint	mɪnt	Minze		
		haunt	hɔnt	verfolgen		
		hunt	hʌnt	Jagd		
	German	Wind	vɪnt	wind		
		Hund	hʊnt	dog		
		Kind	kɪnt	child		
		Hand	hant	hand		
		hin	hɪn	to		
		Rind	ʁɪnt	beef		
		hinter	hɪntɐ	behind		
hire	English	buyer	baɪər	Käufer		
heuern		hide	haɪd	verstecken		
		height	haɪt	Höhe		
		wire	waɪər	Draht		
		tyre	taɪər	Reifen		
		high_hi	haɪ	hoch, hallo		
	German	Hacker	hakɐ	hacker		
		Hammer	hamɐ	hammer		
		Hai	haɪ	shark		
		Feier	faɪɐ	party		
		Leier	laɪɐ	lyre		
		Geier	gaɪɐ	vulture		
		Heil	haɪl	intact, healed		
		Heiler	haɪlɐ	healer		
		heim	haɪm	home		
		heiß	haɪs	hot		
		heiter	haɪtɐ	cheerful		
		heiser	haɪzɐ	hoarse		
hour_our	English	owl	aʊl	Eule		
Stunde, unser/e		out	aʊt	aus, raus		
		sour	saʊər	sauer		
	German	Aua	aʊɐ	ouch		
		Au	aʊ	meadowland		
		Affe	afə	monkey		
		alle	alə	all		
		Amme	amə	nurse		
		Auge	aʊgə	eye		
		aus	aʊs	out		
		auch	aʊx	also		
		Asche	aʃə	ash		
		auf	aʊf	on		
how	English	now	naʊ	jetzt		
wie		wow	waʊ	wau		
		cow	kaʊ	Kuh		
		house	haʊs	Haus		
		high_hi	haɪ	hoch, hallo		
	German	Tau	taʊ	dew		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
		Sau	zaʊ	sow (pig)		
		Hahn	han	rooster		
		Hang	haŋ	slope		
		Au	aʊ	meadowland		
		Bau	baʊ	construction, building		
		Hall	hal	Echo		
		Haar	ha	hair		
		Hass	has	hate		
		Haut	haʊt	skin		
		Hauch	haʊx	breath		
		lau	laʊ	lukewarm		
		Schau	ʃaʊ	show		
		Haus	haʊs	house		
		Hai	haɪ	shark		
		rau	ʁaʊ	rough		
kind	English	find	faɪnd	finden		
freundlich		mind	maɪnd	Geist		
	German	keiner	kaɪnɐ	no one		
		kein	kaɪn	no		
	Pseudo neighbors	pint (Engl.)	paɪnt	(N/A)		
		Feind (Germ.)	faɪnt	enemy		
		Kind (Germ.)	kɪnt	child		
left	English	lift	lɪft	heben		
links, verlassen		Let	lɛt	lassen		
		theft	θɛft	Diebstahl		
	German	Luft	lʊft	air		
		Heft	hɛft	booklet		
		Lift	lɪft	elevator		
		Loft	lɔft	Loft		
lost	English	last	læst	letzte/r		
verloren		cost	kɔst	Kosten		
		loss	lɔs	Verlust		
		list	lɪst	Liste		
		least	list	wenigsten, mindestens		
	German	Rost	ʁɔst	rust		
		Lust	lʊst	desire		
		Lord	lɔɐt	lord		
		Loft	lɔft	Loft		
		Last	last	load		
		Post	pɔst	post, mail		
		Ost	ɔst	East		
		List	lɪst	trick		
loud	English	cloud	klaʊd	Wolke		
laut		load	loʊd	Last		
		aloud	əlaʊd	laut		
	German	Laus	laʊs	louse		
		lau	laʊ	lukewarm		
		Lauer	laʊɐ	lurking		
		laut	laʊt	loud	yes	
		Lauf	laʊf	run		
		Laub	laʊp	foliage		
	Pseudo neighbors	route (Engl.)	raʊt	Strecke		
		shout (Engl.)	ʃaʊt	Ruf		
		out (Engl.)	aʊt	aus, raus		
		doubt (Engl.)	daʊt	Zweifel		
		Land (Germ.)	lant	land		
		Last (Germ.)	last	load		
		Haut (Germ.)	haʊt	skin		
melt	English	meant	mɛnt	gemeint		
schmelzen		belt	bɛlt	Gürtel		
	German	mild	mɪlt	mild		
		Geld	gɛlt	money		
		Feld	fɛlt	field		
		Mehl	mel	flour		
		Welt	wɛlt	world		
		Held	hɛlt	hero		
mess	English	miss	mɪs	vermissen		
Chaos		less	lɛs	weniger		
		mass	mæs	Masse		
		messy	mɛsi	unordentlich		
		guess	gɛs	Schätzung		
		yes	jɛs	ja		
	German	Mass	mas	measure		
		Messe	mɛsə	fair		
		Messer	mɛsɐ	knife		
		Mehl	mel	flour		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
		mies	mis	lousy		
		es	ɛs	it		
		Moos	mos	moss		
mile	English	mail_male	meɪl	Post, männlich		
Meile		may	maɪ	könnte		
		might	maɪt	könnte		
		file	faɪl	Datei		
		mine	maɪn	Mine		
		pile	paɪl	Stapel		
		while	waɪl	während		
		smile	smaɪl	lächeln		
	German	mal_Mahl	mal	times, meal		
		Beil	baɪl	hatchet		
		Keil	kaɪl	wedge		
		geil	gaɪl	cool, good		
		heil	haɪl	intact, healed		
		Meile	maɪlə	mile	yes	
		Mais	maɪs	corn		
		Seil	zaɪl	rope		
		weil	vaɪl	because		
		Teil	taɪl	part		
		Maul	maʊl	mouth		
mint	English	minute	mɪnət	Minute		
Minze		meant	mɛnt	gemeint		
		mist	mɪst	Nebel		
		hint	hɪnt	Hinweis		
	German	Mond	mont	moon		
		Mund	mʊnt	mouth		
		Rind	ʁɪnt	beef		
		Mist	mɪst	gargabe		
		Wind	vɪnt	wind		
		Kind	kɪnt	child		
		mild	mɪlt	mild		
		mit	mɪt	with		
mouth	English	mouse	maʊs	Maus		
Mund		South	saʊθ	Süden		
	German	Maul	maʊl	mouth	yes	
		Mauer	maʊɐ	wall		
		Maus	maʊs	mouse		
now	English	wow	waʊ	wau		
jetzt		cow	kaʊ	Kuh		
		how	haʊ	wie		
		no_know	noʊ	nein, wissen		
		noun	naʊn	Nomen		
	German	Narr	na	fool		
		nass	nas	wet		
		nach	nax	after		
		lau	laʊ	lukewarm		
		Schau	ʃaʊ	show		
		rau	ʁaʊ	rough		
		Tau	taʊ	dew		
		Sau	zaʊ	sow (pig)		
		Bau	baʊ	construction, building		
		Au	aʊ	meadowland		
		Naht	nat	seam		
		nah	na	near		
		nahe	nahə	near		
ought	English	all	ɔl	alles		
sollte		off	ɔf	aus		
		at	æt	bei		
		eat	it	essen		
		it	ɪt	es		
		caught	kɑt	gefangen		
		thought	θɔt	Gedanke, gedacht		
	German	Ost	ɔst	East		
		Ort	ɔɐt	place		
		ob	ɔp	whether		
		oft	ɔft	often		
		Gott	gɔt	God		
		Otter	ɔtɐ	otter		
		Pott	pɔt	pot		
out	English	hour_our	aʊər	Stunde, unser/e		
aus, raus		owl	aʊl	Eule		
		outer	aʊtər	äußere/r		
		doubt	daʊt	Zweifel		
		shout	ʃaʊt	Ruf		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
		put	pʊt	setzen, stellen, legen		
		route	rut	Strecke		
		foot	fʊt	Fuß		
	German	Autsch	aʊtʃ	ouch		
		auch	aʊx	also		
		acht	axt	eight		
		Ast	ast	branch		
		Au	aʊ	meadowland		
		Aua	aʊɐ	ouch		
		auf	aʊf	on		
		Haut	haʊt	skin		
		laut	laʊt	loud		
		Abt	abt	abbot		
		Art	at	type		
		Schutt	ʃʊt	debris		
		Eid	aɪt	oath		
		Akt	akt	act		
		alt	alt	old		
		Amt	amt	office		
		aus	aʊt	out	yes	
		Auto	aʊtə	car		
owl *Eule*	English	hour_our	aʊər	Stunde, unser/e		
		out	aʊt	aus, raus		
		towel	taʊəl	Handtuch		
		wool	wʊl	Wolle		
		vowel	vaʊəl	Vokal		
		pull	pʊl	ziehen		
		bull	bʊl	Bulle		
		foul	faʊl	Verstoß		
		full	fʊl	voll		
	German	Aal_all	al	eel, space		
		Aula	aʊlɐ	auditorium		
		faul	faʊl	lazy		
		aus	aʊs	out		
		auch	aʊx	also		
		Au	aʊ	meadowland		
		Aua	aʊɐ	ouch		
		auf	aʊf	on		
		Gaul	gaʊl	horse		
		Null	nʊl	zero		
		Maul	maʊl	mouth		
piece_peace *Stück, Frieden*	English	pea	pi	Erbse		
		purse	pɜrs	Geldbeutel		
		pass	pæs	Pass		
		niece	nis	Nichte		
		peel	pil	schälen		
		peek_peak	pik	gucken, Spitze		
	German	fies	fis	nasty		
		dies	dis	this		
		Spieß	ʃpis	pike		
		Pier	piɐ	pier		
		Pieps	pips	beep		
		Piep	pip	beep		
		Pass	pas	pass		
		Kies	kis	gravel		
		mies	mis	lousy		
pile *Stapel*	English	pine	paɪn	Kiefer		
		while	waɪl	während		
		pale	peɪl	blass		
		pipe	paɪp	Rohr		
		pie	paɪ	Kuchen		
		mile	maɪl	Meile		
		file	faɪl	Datei		
		pill	pɪl	Pille		
	German	Seil	zaɪl	rope		
		Pfeil	pfaɪl	arrow		
		Teil	taɪl	part		
		weil	vaɪl	because		
		Keil	kaɪl	wedge		
		geil	gaɪl	cool, good		
		heil	haɪl	intact, healed		
		Beil	baɪl	hatchet		
shift *Schicht*	English	gift	gɪft	Geschenk		
		lift	lɪft	heben		
	German	Schiff	ʃɪf	ship		
		Schicht	ʃɪxt	shift	yes	

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
		Schild	ʃɪlt	sign		
		Schrift	ʃʁɪft	writing		
		Stift	ʃtɪft	pen		
		Gift	gɪft	poison		
		Lift	lɪft	elevator		
		Schuft	ʃʊft	villain		
shoot	English	suit	sut	Anzug		
schießen		sheet	ʃit	Laken		
		root	rut	Wurzel		
		shirt	ʃɜrt	Hemd		
		shot	ʃɑt	Schuss		
		shut	ʃʌt	geschlossen		
		shoe	ʃu	Schuh		
	German	Wut	vut	anger		
		Schuh	ʃu	shoe		
		Hut	hut	hat		
		Schub	ʃup	thrust		
		Schutt	ʃʊt	debris		
		gut	gut	good		
		Mut	mut	courage		
		Shirt	ʃœɐt	shirt		
shout	English	route	raʊt	Strecke		
rufen		out	aʊt	aus, raus		
		doubt	daʊt	Zweifel		
	German	Schacht	ʃaxt	shaft		
		Schaum	ʃaʊm	foam		
		Schau	ʃaʊ	show		
		laut	laʊt	loud		
		Haut	haʊt	skin		
		Schutt	ʃʊt	debris		
		Schauer	ʃaʊɐ	shower		
talk	English	toy	tɔɪ	Spielzeug		
reden, sprechen		tech	tɛk	Technik		
		walk	wɔk	Spaziergang, gehen		
	German	Schock	ʃɔk	shock		
		Stock	ʃtɔk	stick		
		Tag	tak	day		
		toll	tɔl	great		
		Dock	dɔk	dock		
		Bock	bɔk	buck		
		Rock	ʁɔk	skirt		
time	English	dime	daɪm	cent		
Zeit		tie	taɪ	binden		
		tyre	taɪər	Reifen		
		tide	taɪd	Gezeiten		
		type	taɪp	Art		
		tight	taɪt	eng		
	German	heim	haɪm	home		
		Teich	taɪx	pond		
		Leim	laɪm	glue		
		Teil	taɪl	part		
		Reim	ʁaɪm	rhyme		
		Teig	taɪk	dough		
		Keim	kaɪm	germ, seed		
town	English	towel	taʊəl	Handtuch		
Stadt		tower	taʊər	Turm		
		noun	naʊn	Nomen		
		down	daʊn	unten		
		tone	toʊn	Ton		
	German	Zaun	tsaʊn	fence		
		Tausch	taʊʃ	swap, trade		
		taub	taʊp	deaf		
		tau	taʊ	dew		
		Faun	faʊn	faun		
tube	English	to_too_two	tu	zu, auch, zwei		
Röhre, Tube		tool	tul	Werkzeug		
		tomb	tum	Grab		
		tooth	tuθ	Zahn		
	German	Tour	tuɐ	tour		
		tun	tun	do		
		Tuba	tubɐ	tuba		
		Tube	tubə	Röhre, Tube	yes	
	Pseudo neighbors	Soup (Engl.)	sup	Suppe		
		taub (Germ.)	taʊp	deaf		
		Tipp (Germ.)	tɪp	tip		
vet	English	set	sɛt	setzen		

(*continued on next page*)

Table A (*continued*)

Target	Language	Neighbor	IPA	Translation	Cognate	Pseudo words/ IPA
Tierarzt		debt	dɛt	Schulden		
		Let	lɛt	lassen		
		pet	pɛt	Haustier		
		get	gɛt	bekommen		
		yet	jɛt	noch		
		wet	wɛt	nass		
		bet	bɛt	Wette		
		net	nɛt	Netz		
	German	weh	ve	hurt		
		fett	fɛt	fat		
		Watt	vat	watt, mud flats		
		Bett	bɛt	bed		
		nett	nɛt	nice		
		Welt	vɛlt	world		
		wenn	vɛn	if		
		wert	veɐt	worth		
		Wetter	vɛtɐ	weather		
		Wut	vut	anger		
		wer_Wehr	veɐ	who, defense		
zoo	English	do	du	tun		
Zoo		sue	su	klagen		
		new	nu	neu		
		who	hu	wer		
		you	ju	du		
		to_too_two	tu	zu, auch, zwei		
		shoe	ʃu	Schuh		
	German	Ruh	ʁu	rest		
		Kuh_Coup	ku	cow, coup		
		so	zo	so		
		Sie	zi	you, they		
		See	ze	lake		
		Schuh	ʃu	shoe		
		du	du	you, they		

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2025.105863.

Data availability

I have included the data as supplementary material

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