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Behavioral and neurophysiological investigations on the bimodal processing of orthography and phonology in spoken word recognition – the effect of orthographic depth

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Für meine Mama –
Du fehlst mir

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Abstract

German

Der Erwerb orthographischer Repräsentationen führt zu einer Veränderung der sprachlichen Organisation des Gehirns. Orthographische Wortformen müssen mit bereits bestehenden phonologischen Wortformen und der zugehörigen semantischen Repräsentation in Beziehung gesetzt werden. Diese Umstrukturierung des mentalen Lexikons führt dazu, dass orthographische und phonologische Informationen nicht unabhängig voneinander verarbeitet werden, sondern sich gegenseitig beeinflussen. Weitreichende Untersuchungen zeigen, dass phonologische Informationen beim Lesen in alphabetischen Schriftsystemen automatisch aktiviert werden. In ähnlicher Weise erbrachte eine neuere Forschungsrichtung Evidenz für eine ebenso automatische Aktivierung orthographischer Informationen bei der Verarbeitung gesprochener Wörter. Sprachverarbeitung ist somit bimodal unabhängig von der Modalität des sprachlichen Inputs. Die existierende Literatur zur bimodalen Verarbeitung gesprochener Wörter beschränkt sich jedoch auf das Englische und Französische, zwei Sprachen, die als orthographisch tief gelten. Die orthographische Tiefe gilt als das wichtigste Konzept zur Erklärung zwischensprachlicher Unterschiede in allen Verarbeitungsprozessen, die in Relation zum orthographischen System stehen. Die vorliegende Dissertation untersucht daher, ob sich die orthographische Tiefe eines Schriftsystems auch auf die bimodale Verarbeitung gesprochener Wörter auswirkt. Zwei Studien mit mehreren Experimenten werden berichtet, in denen späte deutsch-englische Bilinguale unter Verwendung behavioraler und neurophysiologischer Methoden in ihrer Erst- und Zweitsprache untersucht wurden. Die Ergebnisse beider Studien liefern Evidenz für einen substanziellen Einfluss der orthographischen Tiefe auf die bimodale Wortverarbeitung. Sowohl die Art als auch das Ausmaß des Einflusses variierten systematisch mit der orthographischen Tiefe der Zielsprache. Orthographische Informationen führten zu Verarbeitungserleichterungen im Englischen, aber zu einer erschwerten Verarbeitung im Deutschen. Orthographische Informationen wirkten früher, länger und stabiler auf die Verarbeitung gesprochener Wörter im Englischen ein, während phonologische Informationen für das Deutsche eine größere Bedeutung zeigten. Diese Ergebnisse deuten somit darauf hin, dass die bimodale Verarbeitung gesprochener Wörter durch die orthographische Tiefe des Schriftsystems moduliert wird. Sie zeigen außerdem, dass späte Bilinguale Verarbeitungsmechanismen flexibel an die Zielsprache anpassen. Die Ergebnisse stehen im Einklang mit Modellen zur bimodalen Wortverarbeitung wie dem *Bimodal Interactive Activation Model* (BIAM).

English

The acquisition of orthographic representations leads to a restructuring of the organization of language in the brain. Orthographic word forms need to be connected to existing phonological word forms and the corresponding semantic representations. This restructuring of the mental lexicon leads to interdependent orthographic and phonological representations. As a consequence, extensive studies show that phonological information is automatically activated in reading in alphabetic writing systems. In the same way, a more recent line of research found evidence for a similarly automatic activation of orthographic information in spoken word recognition. Hence, language processing is bimodal in nature irrespective of the modality of the linguistic input. However, the existing literature on the bimodal processing of spoken words is limited to English and French, two languages that are considered orthographically deep. Orthographic depth is regarded as the most relevant concept for the explanation of cross-linguistic differences in all orthographically related processing. Therefore, the current thesis investigates if the orthographic depth of a writing system also influences the bimodal processing of spoken words. Two studies with several experiments are described in which late German-English bilinguals were investigated in their native and their second language. The findings of both studies provide consistent evidence for a substantial influence of orthographic depth on bimodal word processing. Both the nature and the extent of this influence systematically varied as a function of the orthographic depth of the target language. Orthographic information led to facilitated processing in English, but inhibited processing in German. Orthographic information showed earlier, longer lasting, and more stable influences on spoken word recognition in English, while phonological influences were prevalent in German. These findings, thus, indicate that the bimodal processing of spoken words is modulated by the orthographic depth of the writing system. They also show that late bilinguals flexibly adapt processing mechanisms to the target language. The results are in line with models of bilingual word recognition such as the Bimodal Interactive Activation Model (BIAM).

1. General introduction

Learning to read requires the mapping of abstract visual symbols (graphemes) onto single units of spoken language (phonemes) with the goal to retrieve a word's meaning. In languages such as English, the relationship between the visual symbol and the sound is systematic, while the relationship between the symbol and its meaning is arbitrary. By learning the relationship between symbol and sound, the so-called grapheme-phoneme-correspondences, children can derive a word's phonology from its written from and access the word's meaning (Ziegler & Goswami, 2005). A child's knowledge about the phonological properties of spoken word forms, termed phonological awareness, is widely considered the pre-requisite for reading acquisition. However, it has also been found that the acquisition of reading leads to phonemic awareness, illustrating an interactive relationship between the knowledge about phonemes and graphemes (Goswami, 2002). This demonstrates that the connections between phonology and orthography are highly dynamic and that both systems influence each other not only during reading acquisition and the processing of written language, but – as has been reliably shown over the last decades – also during spoken word recognition. This makes word recognition a bimodal process involving both orthographic and phonological representations, irrespective of the input modality. However, the relationship between phonology and orthography is not always straightforward. In English, grapheme-phoneme-correspondences are highly complex and unpredictable, which has wide-ranging consequences for the processing of phonological and orthographic information. The vast research on cross-linguistic reading behavior shows that the nature of grapheme-phoneme-correspondences is the most significant predictor for differences in reading-related behavior between languages (e.g., Goswami, 2002, 2010; Landerl et al., 1997; Rau et al., 2015; Schmalz et al., 2015; Seymour et al., 2003; Wimmer & Goswami, 1994; Ziegler & Goswami, 2005).

In this thesis, I will show that the complexity and consistency of grapheme-phoneme-correspondences, termed orthographic depth, not only influences visual word recognition and reading, but also substantially modulates the interaction of phonology and orthography during spoken word recognition. In the following introduction I will first provide an overview over empirical evidence and theoretical assumptions underlying the dynamic interaction between the two modalities, which will illustrate that spoken word processing is bimodal in nature. I will then focus on the concept of orthographic depth and its significance for phonological and orthographic processing as shown by the rich research of reading. Lastly, I will discuss neurophysiological correlates of orthographic and phonological processing, before introducing two series of experiments I conducted to provide evidence for the effect of orthographic depth on the bimodal processing of orthography and phonology in spoken word recognition.

1.1 The bimodal processing of orthography and phonology

> When we become literate, it has been argued that the orthographic processes required for reading simply make use of the existing spoken word recognition system via the recoding of orthography into phonology. Such an account assumes that the phonological representation that mediates between an orthographic stimulus and its meaning is the same as that mediating between an acoustic stimulus and its meaning. From this description, then, there is no reason to suppose that the introduction of orthography into the lexical processing system would have any impact at all on the recognition of spoken words. Orthographic processing is merely appended to the extant spoken word recognition system. There is increasing evidence, however, that orthographic information does have an impact on spoken word processing, and this has been demonstrated using a range of different auditory tasks […]. (Taft et al., 2008, p. 366-367)

Over the course of their development, the vast majority of individuals acquire linguistic representations in two modalities – in spoken and in written form. It has long been the assumption that the spoken modality is the primary form of language because it precedes written language both in the history of mankind and the individual's development. Scripts used for communication have only been established a couple of thousand years ago. Literacy among the broad population is even more recent considering that access to written language among the general public was only established in the 19th century in Europe and even later on a global scale (Roser & Ortiz-Ospina, 2016). Moreover, individuals usually acquire written language at an age when the spoken modality is already well developed. The view that the spoken form of language is the natural and, hence, dominant modality also found its way into linguistic theories with researchers arguing that the phonological system, established well in advance of the orthographic system, is the core structure for language processing even for reading (Frost, 1998; Lukatela, et al., 1993; van Orden, 1987). The dominance of the phonological system was challenged when it became clear that the accommodation of written representations of word forms in the mental lexicon had more far-reaching consequences than previously assumed. Increasing evidence shows that the mental lexicon is highly dynamic allowing for complex interactions between phonological and orthographic representations in language processing both in the spoken and written modality (e.g., Chérau et al., 2007; Coltheart, 2001; Harm & Seidenberg, 2004; Rastle & Brysbaert, 2006; Taft et al., 2008; Ziegler & Ferrand, 1998).

In the following section, I will first reflect theoretical assumptions and empirical evidence on the roles of phonology in reading and orthography in spoken word processing, which will show that word processing is, in fact, bimodal in nature involving both phonological and orthographic representations irrespective of the input modality. Following this, I will discuss two accounts that seek to explain how representations in the mental lexicon are organized in order to enable bimodal word processing, the phonological specification and the co-activation account. I will provide evidence in favor of the latter theory and will conclude this part of the thesis with the in-depth description of a psycholinguistic model that implements the assumptions of the co-activation account, the Bimodal Interactive Activation Model. I will use this model to illustrate the assumed mechanisms underlying bimodal word processing which will be the basis for the hypotheses of my own empirical studies in the second part of this thesis.

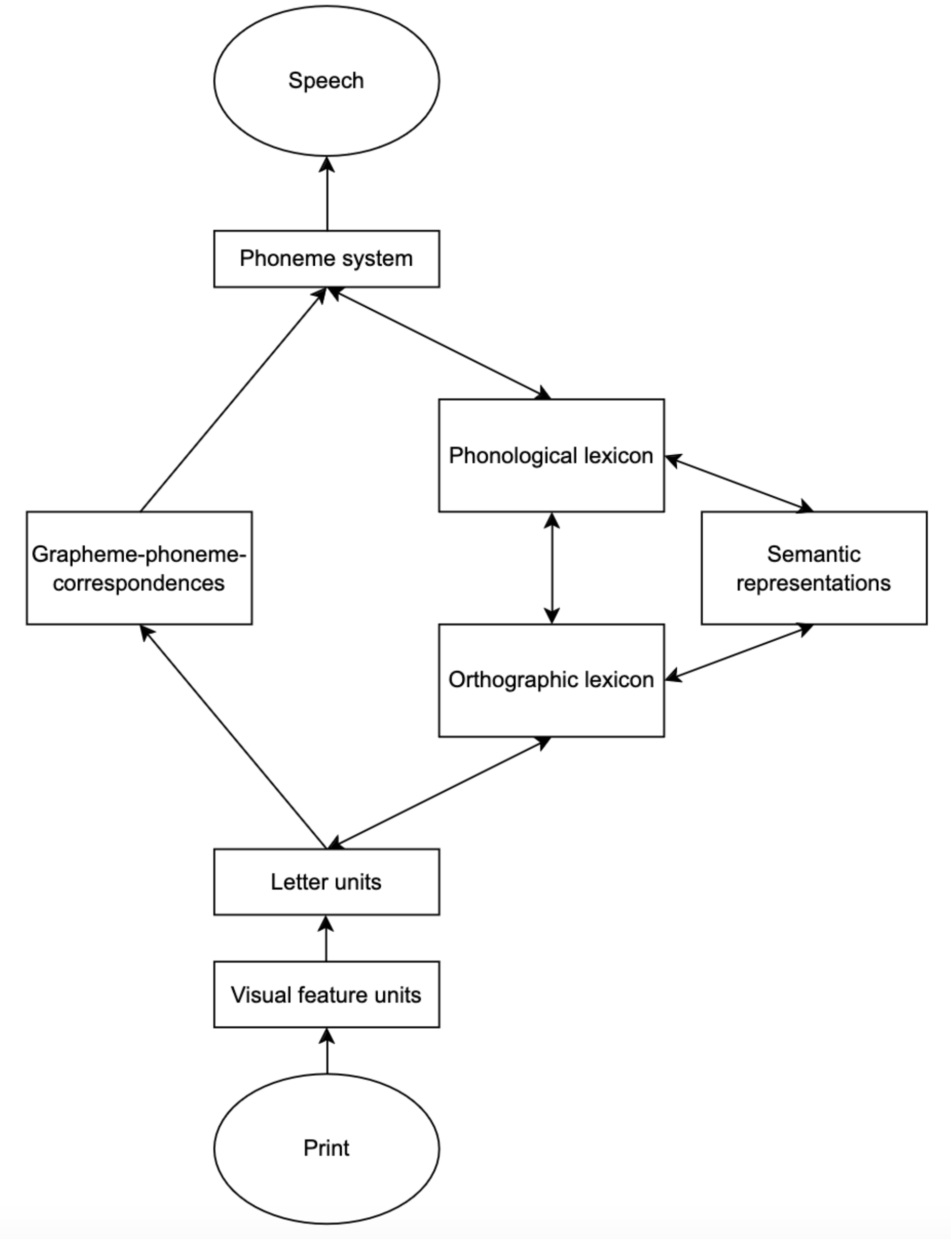
1.1.1 Phonology in reading

Alphabetic writing systems reflect the sounds of the spoken language. Abstract symbols composed of curves and lines need to be connected to one or more sounds of the language these letters represent. Thus, a connection is established between the abstract letter or letters and the phoneme or phonemes associated with them. Because the phonological system is already well established when written language is acquired, it has been argued that orthography is a "secondary system [that] is appended parasitically onto the already existing [phonological] system" (Frost, 1998, p. 74). This so-called "Speech Primary Axiom" states that a connection between orthography and meaning is mediated by phonology, which implies that reading without activating phonological representations is impossible, at least in alphabetic languages. This strong phonological theory of reading thus proposes that no direct links between orthography and semantic representations exist and any access of a word's meaning must involve phonology. Moreover, this account assumes that reading is primarily a phonological task and that many reading-related processes mostly rely on phonological representations rather than orthographic representations (Frost, 1998; Lukatela, et al., 1993; van Orden, 1987).

Opposingly, dual-access models suggest a route involving phonology via grapheme-phoneme correspondences, often called the "indirect" route, and a route connecting orthographic representations directly to semantic meaning without the need for phonological recoding processes ("direct route"). One of the most established dual access models is the Dual-Route Cascaded model of visual word recognition and reading aloud (DRC; Coltheart et al., 2001). The DRC is a computational model meaning that the model assumptions are mathematically implemented and can be used to simulate the reading process and to test hypotheses about reading-related behaviors. Figure 1 illustrates the basic architecture of the DRC model.

Figure 1

Basic architecture of the Dual-Route Cascaded Model



Note. Adapted from Coltheart et al. (2001).

The nature of the connections (excitatory, inhibitory) between model components are omitted in the figure. Please see Coltheart et al. (2001) for further information.

According to the DRC, exposure to print activates corresponding units of visual features connected to specific letters. All letters containing the activated visual features are activated in turn. The core assumption of dual route models like the DRC is that reading takes place via two different routes: The indirect route involving conversion of the letter string into a sequence of phonemes via the application of grapheme-phoneme-correspondence rules and the direct route which maps whole word orthographic word forms stored in the orthographic lexicon onto whole word phonology stored in the phonological lexicon. The DRC model assumes that skilled word reading is based on whole word orthography via the direct route. The indirect route is primarily used for reading non-words. Word reading via the direct route can involve access to semantic representations, however, this is not necessary if the goal is not reading for meaning but rather the pronunciation of a word. Contrary to strong phonological accounts, a direct link between orthographic word forms and the semantic meaning is assumed, thus, reading for meaning is not mediated by phonology. The DRC model represents a so-called "weak phonological theory" as opposed to the strong phonological account described above. Weak phonological accounts propose that reading is primarily based on orthographic representations with the involvement of phonology being viewed as secondary (Coltheart et al., 2001; Rastle & Brysbaert, 2006). For visual word processing, strong phonological models assume that there is no direct link between letter units and orthographic knowledge, instead, this relationship is mediated by phonology. Weak phonological accounts refute this claim and propose a direct link between letter units and orthographic knowledge. In the DRC model, this is illustrated by a direct link between the letter units and the orthographic lexicon. Phonology is indirectly involved via a link between letter units and grapheme-phoneme-correspondences (Coltheart et al., 2001).

Frost (1998) suggests that the strong phonological theory can be corroborated by showing an involvement of phonological processing even when it is not necessary or even a hindrance to the task at hand. If phonology is involved in a task in which it is not explicitly needed, this would affirm that phonological representations are a necessity for the processing of written information and are activated automatically. One paradigm that illustrates this effect is the speech detection paradigm. In a series of experiments, participants were presented with speech masked by noise and noise-only trials accompanied by matching or non-matching print. The amplitude envelope of the noise matched the amplitude envelope of the speech. When a printed word matched the speech signal it also matched the amplitude envelope of the noise. The result was an auditory illusion: Participants reported to hear the speech in the signal even when it was not present when the noise amplitude envelope matched the print. Participants were explicitly informed that the print might hinder the correct detection of speech or noise-only. Nonetheless, the matching print reliably produced the illusion of speech in the noise-only trials (Frost, 1991; Frost et al.,1988). This is taken as evidence that phonetic recoding in silent reading is rapid and mandatory even in a task when doing so is detrimental to performance. Similar effects can be found in a letter search task. In this task, participants are presented with a letter string, e.g., *brane*, and are asked whether they can detect the letter *i* in that letter string. Even though this task does not require any involvement of phonetic-phonological representations, a pseudohomophone disadvantage was shown. Participants reported more false alarms for letter strings that have a homophone that contains the target letter (e.g., *brane – brain*) compared to letter strings that do not have such a homophone (Ziegler & Jacobs, 1995; Ziegler, van Orden & Jacobs, 1997). This illustrates a fast activation of phonological code in visual word recognition even if the task only requires graphemic information. The pseudohomophone *brane* activates the corresponding phonological code which in turn activates the connected orthographic representation that does contain the target letter, thus interfering with task performance.

However, Rastle and Brysbaert (2006) show evidence against the argument made by Frost (1998) that the fast and automatic activation of phonology in visual word processing is not compatible with a weak phonological account of reading. They argue that "[u]nder normal reading conditions, phonological processing *always* occurs" (Rastle & Brysbaert, 2006, p. 101; highlighting done by authors). Moreover, they note that just because phonology is rapidly and automatically involved in visual word recognition does not prove that it is a necessity for reading. They show that masked phonological priming, a task previously argued by strong phonological theorists to provide convincing evidence for a strong phonological account, is under certain constraints compatible with the DRC model. Phonological priming of visual words occurs when recognition of a visual target word (e.g., *clip*) is facilitated by the previous presentation of a pseudohomophone (a non-word that is phonologically similar to the target) (e.g., *klip*) compared to a control prime (e.g., *plip*). Phonological priming in visual word recognition has been reported with very brief presentation durations and masking of the prime. The prime is presented so briefly that the participants are not aware of its presence and cannot report it. This is assumed to indicate a very fast and automatic (i.e., unconscious) influence of phonology in visual word recognition and has been used as a primary argument for a strong phonological account. However, masked phonological priming effects can in principle be simulated with the DRC model even though radical changes to the standard model parameters are necessary (Coltheart & Rastle, 1994; Rastle & Brysbaert, 2006). Moreover, other often observed effects of phonology on visual word processing such as homophone and pseudohomophone effects on lexical or semantic decision have been reconciled with a weak phonological account of reading (Coltheart & Rastle, 1994; Coltheart et al., 2001; Harm & Seidenberg, 2004).

Van Orden (1987) presented participants with a semantic categorization task. A category name (e.g., “a flower”) was presented on a screen and participants had to decide whether the following target word was a category member or not. In critical trials, a homophone of a category member was presented (e.g., *rows* instead of *rose*). Participants made significantly more false positive errors when the target word was a homophone of a category member than for spelling controls (e.g., *robs*). This effect was still present when the target word was masked from conscious processing, i.e., when the participants reported not seeing the word. While effects of spelling affected false positive answers when the target was unmasked, masking led to equal false positive rates for similarly and dissimilarly spelled homophones. These findings are taken as evidence for fast, automatic involvement of phonology in semantic access and are argued to dispute a direct connection between orthography and semantics in favor of a phonologically mediated semantic access in agreement with the strong phonological account.

However, Harm and Seidenberg (2004) used a weak phonological computational model to simulate the experiments by van Orden (1987). Their model involves a semantic, an orthographic, and a phonological component that are directly connected to each other. Mapping from orthography onto semantic meaning can either take place directly (orthography → semantics), indirectly via mediation by phonology (orthography → phonology → semantics), or both. Using the same stimuli as van Orden (1987), the authors found the exact same pattern of results produced by their weak phonological model as was observed by the behavior of participants in van Orden’s study. This is evidence that the fast and automatic influence of phonology on semantic categorization of visually presented words is in agreement with a weak phonological account. At the same time, Harm and Seidenberg (2004) provide evidence that stands in opposition to a strong phonological theory of reading. They simulated reading of 497 pairs of homophones with their model while all routes were intact and when routes were impaired. Accuracy of semantic mapping of the homophones was severely reduced when only the indirect route to semantics mediated by phonology was enabled and the direct route was impaired, because of the high phonological ambiguity of homophones. Contrarily, when semantic mapping of homophones took place via the direct connection between orthography and semantics, high accuracy values were achieved. Accuracy was highest when the model was intact, i.e., when the direct and indirect route to semantics could both contribute to the task. This is in direct contradiction to the assumption of strong phonological theorists that access from orthography to semantics must always be mediated by phonology.

In sum, the findings presented in this section provide ample evidence for a fast and automatic activation of phonology in reading. The influence of phonological representations in visual word processing is undisputed in the literature. However, core assumptions of the strong phonological account of reading cannot be upheld in the face of current evidence. The assumption that reading is primarily a phonological process and orthography is a secondary, parasitic system must be disputed. Rather, it can be assumed that reading recruits both orthographic and phonological representations with a direct route involving whole word orthographic representations that can be mapped onto semantic meaning and an indirect route that involves phonology and explains phonological influences in reading as suggested by weak phonological accounts such as the DRC model. This makes visual word processing a bimodal process, because it involves representations of both the spoken and the written modality of language. Moreover, if orthography was a secondary system that was merely appended to phonology and reading was primarily a phonological task, there is no reason to assume that orthography should have any impact on the processing of spoken words. However, there is extensive evidence that suggests the involvement of orthography in spoken word recognition to be as automatic as the activation of phonology in visual word recognition.

1.1.2 Orthography in spoken word processing

The seminal study that first demonstrated an influence of orthography on spoken word processing was conducted in 1979 by Seidenberg and Tanenhaus. Participants were auditorily presented with a cue word followed by the auditory presentation of a list of words. They had to identify the one word in the list that rhymed with the cue word. Latencies for the detection of the rhyming word were recorded. The critical manipulation lay in the orthographic overlap between cue and rhyming word. Rhymes were either orthographically similar to the cue (e.g., *pie – tie*) or orthographically dissimilar (e.g., *rye – tie*). Participants identified the rhyme word significantly faster if rhyme and cue overlapped orthographically than when they were orthographically dissimilar even though both the cue and the word list were only administered auditorily. Further evidence for orthographic influences in phonological tasks has been observed in syllable segmentation (Morais et al., 1989), phoneme monitoring (Dijkstra et al., 1995; Frauenfelder et al., 1990) or syllable monitoring (Taft & Hambly, 1985).

However, these tasks are "meta-phonological" in nature meaning that they explicitly require the recruitment of phonological information to solve the task, for example, the knowledge about what a rhyme is and what characteristics make two words rhyme. It has long been observed that the acquisition of orthography shapes individuals' abilities to reflect upon the nature of speech and to perceive spoken words as consisting of a series of sounds in the same way as letters make up a written word. This is evident in studies showing that the deletion of phonemes in a word is harder for illiterates than for literates (Morais et al., 1979) or that the number of phonemes in a word is overestimated when the phoneme is represented by more than one grapheme (Ehri & Wilce, 1980). Thus, it has been argued that orthographic effects in meta-phonological tasks such as rhyme monitoring or phoneme deletion might simply be a strategy used by the participants to adequately perform the task and might only play a role at a top-down, post-perceptual level (e.g., Dijkstra et al., 1995; Frauenfelder, 1990; Goswami, 2002).

Ziegler and Ferrand (1998) used words with consistent (e.g., *stage* 'internship') and inconsistent spellings (e.g., *plomb* 'lead') in French and presented them to their participants in an auditory manner. The rime of orthographically consistent words like *stage* (/staʒ/) can only be spelled in one way (*-age* as in *cage* 'cage', *rage* 'rage', *plage* 'beach', etc.), while inconsistent words like *plomb* (/plɔ̃/) can have multiple spellings for the same phonological rime (e.g., *nom* 'name', *prompt* 'rapidly', *ton* 'tone', *tronc* 'trunk', *long* 'long'). The authors found higher reaction times and lower accuracies in a lexical decision task for words with inconsistent spellings compared to words with consistent spellings even though participants never saw a written word form. Because the task was neither meta-phonological in nature nor required the activation of orthographic code, it was argued that the top-down activation of orthography is unlikely and that, hence, the influence of orthography on spoken word processing is automatic. Using the same paradigm with electroencephalography (EEG), a technique that records electric brain activity with high temporal precision, Perre and Ziegler (2008) showed that spelling inconsistencies affect spoken word processing at a sub-lexical level. Earliest effects of consistency were observed 320 ms after stimulus onset for stimuli with a duration of 600 ms. Thus, orthographic consistency had an effect on spoken word processing before the word was fully perceived. Moreover, the consistency effect was time-locked to the position of the inconsistency in the word: The effect showed a higher latency if the inconsistency was found in word-final positions as opposed to word-initial positions. This provides clear evidence that effects of orthography on spoken word processing occur as the auditory stimulus unfolds. Consequently, phonological and orthographic information are activated simultaneously during spoken word recognition and orthographic influences are not limited to a post-lexical, top-drown driven level of processing. The orthographic consistency effect in spoken word processing has since been replicated several times in French and English with different tasks (e.g., Pattamadilok et al., 2010; Peereman et al., 2009; Petrova et al., 2011; Salverda & Tanenhaus, 2010; Ziegler et al., 2004).

One downside to the consistency effect paradigm lies in the fact of different word forms being compared across conditions, e.g., the behavioral and brain responses to the word *stage* (consistent) are compared to those of the word *plomb* (inconsistent). Even though known characteristics that can influence processing such as number of syllables, word frequency, phonological neighborhood, uniqueness point, duration or number of phonemes are controlled between the groups of words, consistent and inconsistent words could differ in a systematic way that is unknown and cannot be controlled, explaining the observed differences. Using an auditory priming paradigm, Chérau, Gaskell and Dumay (2007) showed that rhyming words with orthographic overlap (e.g., *shirt – dirt*) produced lower reaction times and fewer errors compared to rhyming words that did not overlap orthographically (e.g., *hurt – dirt*) in a lexical decision task. Participants were unaware of the orthographic manipulation of the stimuli. Even though no written word form was presented and the recruitment of orthographic information was not required to perform the task, orthography had an effect on spoken word processing. Notably, in this paradigm, the reaction to the same target word is measured in all conditions and the degree of phonological overlap is equal across conditions. Thus, differences between the conditions cannot stem from the word itself or differences in phonological relatedness but must be attributed to the degree of orthographic overlap between prime and target.

This finding was replicated by Perre and colleagues (2009) in a study using both behavioral and EEG measures. The authors showed that words with phonological and orthographic overlap (e.g., *beef – reef*) resulted in lower reaction times, higher accuracies and lower N400 amplitudes compared to words only overlapping phonologically (e.g., *leaf – reef*). Both overlap conditions facilitated processing compared to a non-overlap control condition (e.g., *sick – reef*). Notably, the effect produced by the orthographic overlap and the effect produced by the phonological overlap could be differentiated topographically: the former was located at central electrode sites, while the latter was limited to parietal electrode sites. Strikingly, though, both effects occurred at the same latency, indicating that orthographic and phonological overlap influenced processing of the target word simultaneously.

Taft and colleagues (2008) argue that if similar evidence can be found for orthographic influences on spoken word recognition as has been reported for phonological influences on visual word recognition, it must be assumed that orthography plays as much a role in the processing of spoken words as phonology plays in reading. As described in the previous section, a paradigm often used to show fast and automatic involvement of phonology in visual word recognition is masked pseudohomophone priming. The brief and masked presentation of a pseudohomophone (e.g., *klip*) facilitates processing of a following target word (e.g., *clip*) relative to a control (e.g., *plip*) in the visual modality. In an effort to mirror the evidence found for phonology in reading, Taft et al. (2008) used masked pseudohomograph priming to investigate influences of orthography on spoken word processing. They constructed pseudohomographs, phonological word forms that do not exist in reality but can be spelled in the same way as an existing word, e.g., /dri:d/ can be spelled *dread* in analogy to *bead*, pronounced /bi:d/. Consequently, /dri:d/ should facilitate /dɹɛd/ because they can be spelled identically, namely *dread*, in the same way as *klip* facilitates *clip*, because they can be pronounced identically. A non-homograph control condition was constructed that consisted of non-existent phonological word forms that cannot be spelled in the same way as an existing word (e.g., /ʃɹi:d/ for /ʃɹɛd/, where /ʃɹi:d/ cannot be spelled *shred*, but must be spelled *shread* in analogy to *bead* or *shreed* in analogy to *reed*, etc.). In order to mask the prime from conscious perception, it was embedded in a series of unrelated Vietnamese syllables spoken by a bilingual Vietnamese-English speaker. Participants were instructed that they would hear a string of nonsense sounds followed by a louder voiced target word. They were asked to decide whether the louder utterance was an existing English word or not. The authors found a clear pseudohomograph priming effect: Targets preceded by a pseudohomograph (e.g., /dri:d/ - /dɹɛd/) were responded to faster and more accurate compared to an unrelated control condition, while no difference was found between the non-homograph condition (e.g., /ʃɹi:d/ - /ʃɹɛd/) and an unrelated control condition. Awareness of the prime did not make any difference for the results. Thus, these findings mirror the effects found for phonology in reading and can be taken as evidence for a fast and automatic activation of orthography in spoken word recognition.

Taken together, the findings presented in this section provide convincing evidence that orthography influences spoken word recognition in the same way as phonology influences the processing of visual words. Behavioral and neurophysiological data suggest that orthography is activated in tasks that do not require to reflect upon the phonological or orthographic structure of a word form and does, thus, not indicate purely strategic processes. Findings from studies using EEG show that orthographic information is activated simultaneously with phonological information when an auditory word form is encountered and influences auditory processing at a pre-lexical level. Masked pseudohomograph priming showed that orthographic similarities between prime and target facilitate target processing even when the prime is not consciously perceived. It, therefore, must be concluded that the activation of orthographic information during spoken word processing is as fast and automatic as the involvement of phonological representations in visual word recognition. Therefore, word processing irrespective of the input modality is bimodal in nature. This raises the question of how orthographic and phonological representations are organized in the mental lexicon to enable their simultaneous influence during bimodal word processing.

1.1.3 Co-activation versus phonological specification

The acquisition of written language profoundly changes the organization of the mental lexicon through the accommodation of orthographic representations and their connection to pre-existing phonological units. However, it is a long-standing debate in the literature, how exactly the mental lexicon changes and whether the accommodation of orthographic information affects the nature of the pre-existing phonological representations. The phonological specification account assumes that influences of orthography on spoken word processing can be explained by the alteration of phonological representations during the acquisition of reading. Taft and Hambley (1985) investigated influences of orthography on the phonological representation of words. Based on Chomsky and Halle (1968) they first assume that phonological representations are morphophonemic in nature rather than surface phonemic. This means that phonological representations of a word take into account morphological variants associated with that word form. The surface phonemic representation of the word *metallic* is /mətæl.ɪk/ and thus, the onset contains the reduced vowel /ə/. However, there is a morphologically related word *metal* (/mɛtəl/) whose phonological representation contains the full vowel /ɛ/. The surface phonemic account suggests that if participants are asked to decide whether the word *metallic* starts with /mɛ/ they should be able to refute this, because the phonological representation of the word does not contain the full vowel. However, if phonological representations are morphophonemic, the full vowel of the morphological variant *metal* should be retained in the representation of *metallic* and participants should either incorrectly answer with “yes” or should take a long time to answer “no”.

However, a second explanation could account for the latter possibility: Instead of morphological variants, an orthographic influence on the phonological representation is discussed based on the findings by Seidenberg and Tanenhaus (1979) (Taft, 2006; Taft & Hambley, 1985). The knowledge about the full vowel of the variant *metal* could also stem from the orthographic representation. Moreover, if orthographic information influences phonological representations, participants should also have trouble deciding if the word lagoon (/ləguːn/) starts with /læg/ even though no morphological variant exists that contains the full vowel. To test this assumption, the authors presented participants with auditory words whose first vowel was a reduced vowel (/ə/). Half of the words had a morphological variant containing a full vowel and half of the words did not. Words were preceded by a target phoneme string (e.g., /mɛt/) which consisted of the first two consonants of the word surrounding a vowel of full value. Participants had to decide if the full vowel heard in the phoneme string was present in the following word (e.g., /mɛt/ – /mətæl.ɪk/). Accuracy values showed no difference between words with and without a morphological variant containing the full vowel. Participants tended to respond “yes, the full vowel was heard”, regardless if the word form was *metallic* (having a morphological variant containing the full vowel) or *lagoon* (not having a morphological variant containing the full vowel). The authors conclude that the phonological representation of the word is influenced by orthography, because only from the orthographic code could participants determine the respective full vowel for words that did not have a morphological variant (Taft, 2006; Taft & Hambley, 1985). Taft (2006) suggests that due to the orthographic code schwa is represented mentally as a full vowel so that the phonological representation of /ləguːn/ is actually /læguːn/, where /æ/ is reduced to a schwa when stress is assigned in generating the surface pronunciation.

Muneaux and Ziegler (2004) make a similar argument by suggesting that spelling-to-sound consistency at the sub-lexical level could be used to permanently alter phonological representations at the lexical level, thereby affecting the nature of phonological representations. To test these assumptions, they propose a neighbor generation task and argue that if participants are asked to generate phonological neighbors for a certain word, e.g., *wipe*, there are two ways in which they could likely answer. If orthography alters the representation of phonology, then participants should be more likely to come up with a neighbor that shares both phonological and orthographic features with the target word (i.e., a phonographic neighbor), e.g., *ripe*. However, if orthography does not play a role in the phonological representations, they should be more likely to choose the neighbor with the highest word frequency irrespective of an orthographic overlap between the target word and the neighbor, e.g., *type*. The authors presented participants with spoken words and asked them to generate a similar sounding word (i.e., words that can be obtained by changing, adding, or deleting a phoneme). They found that participants produced a phonographic neighbor significantly more often than would be expected based on type and token frequencies of phonographic neighbors in a database. These results were replicated in a second experiment, in which only words with many phonological neighbors were used, thus reducing the likelihood of an orthographic strategy being used by the participants. The authors argue that this illustrates the alteration of phonological representations during the acquisition of reading and spelling. Consequently, the effect of orthography on spoken word processing is said to arise solely within the phonological system (Taft, 2006; Taft & Hambley, 1985; Taft et al., 2008).

However, a competing theory suggests that the same results can be achieved via simple co-activation of phonological and orthographic representations rather than a restructuring of the phonological code represented in the lexicon. During language processing, representations of both modalities are then activated simultaneously via a strong link between orthography and phonology formed during reading acquisition, thus enabling bimodal processing of the linguistic input in either modality. In fact, Taft (2006) concedes that rather than a restructuring of phonology, the activation of the orthographic representations could also explain how participants have knowledge about the full vowel in the study by Taft and Hambley (1985). Here, the orthographic knowledge could simply be provided by the joint activation of orthographic and phonological representations rather than orthographic knowledge being included in the phonological representation. The assumption that phonological representations are altered is not necessary to explain the findings (see also Taft et al., 2008).

Similarly, one could argue that the generation of phonographic neighbors is not due to the orthographically altered phonological representations, but rather comes from the additional activation of orthography. The co-activation account assumes that orthographic information is co-activated in an on-line fashion during each encounter with a spoken word. Hence, listening to the spoken words provided by Muneaux and Ziegler (2004) would activate the phonological representation and via a link also the connected orthographic representation, which in turn would activate their respective neighbors. Phonographic neighbors would then receive activation from both orthography and phonology, while phonological neighbors without orthographic overlap would only receive activation from phonological representations. For example, presenting the auditory word form /waɪp/ activates the corresponding phonological representation which in turn activates the phonological neighbors /ɹaɪp/ and /taɪp/ in a similar manner because they share the same phonological overlap. Via links between the whole word phonological and orthographic representations, the representation of /waɪp/ feeds activation forward to the orthographic lexicon, co-activating <wipe>, which also activates its neighbors, e.g., <ripe>. Thereby, *ripe* being both a phonological and orthographic neighbor receives activation from both modalities, while *type* only receives activation from phonological representations, because it is not an orthographic neighbor. This can explain why phonographic neighbors are primarily produced by the participants: they have higher activation in the lexicon, because they are activated by corresponding representations of both modalities. Again, the assumption of a restructuring of the underlying phonological representation is not necessary to explain the findings.

Thus, the findings reported above attributed to altered phonological representations can also be explained by a co-activation account. Contrarily to the off-line experiments provided above, on-line investigations using EEG have found that orthographic and phonological priming effects in an auditory task can be differentiated by their neurophysiological correlates (event-related potentials; ERPs), thereby indicating that different mechanisms drive these effects. The study by Perre, Midgley and Ziegler (2009) introduced above used an auditory priming paradigm with a lexical decision task and presented word pairs that overlapped orthographically and phonologically (O+P+; e.g., *beef – reef*), phonologically but not orthographically (O-P+; e.g., *leaf – reef*) or not at all (O-P-; e.g., *sick – reef*). The phonological priming effect evident in a reduced N400 component for both P+ conditions compared to the P- condition could be topographically differentiated from the orthographic priming effect produced by the O+P+ condition compared to the O-P+ condition. The latter showed a central distribution while phonological overlap produced effects at parietal electrode sites. If both effects had been driven by an altered phonological representation, no topographical differences should have occurred, because both effects should have arisen solely within the phonological system. The topographical differences provide evidence for distinct underlying neuronal mechanisms for the two priming effects which is in line with the co-activation hypothesis.

The assumption of a co-activation of orthography and phonology in word processing is famously implemented in the Bimodal Interactive Activation model that will be discussed in the next section, because it is central for the experimental studies presented in this thesis. Even though arguments can be made for both the phonological specification and the co-activation accounts, on-line results seem to be in support for the latter, while the off-line findings can be explained by both. So there does not seem to be a need to assume that the phonological representations underlying bimodal processing are different from the phonological representations that are formed before the acquisition of written language. Rather, the simultaneous activation of phonological and orthographic representations and an assumed strong link between the two can account for the findings and is a better fit for the on-line results.

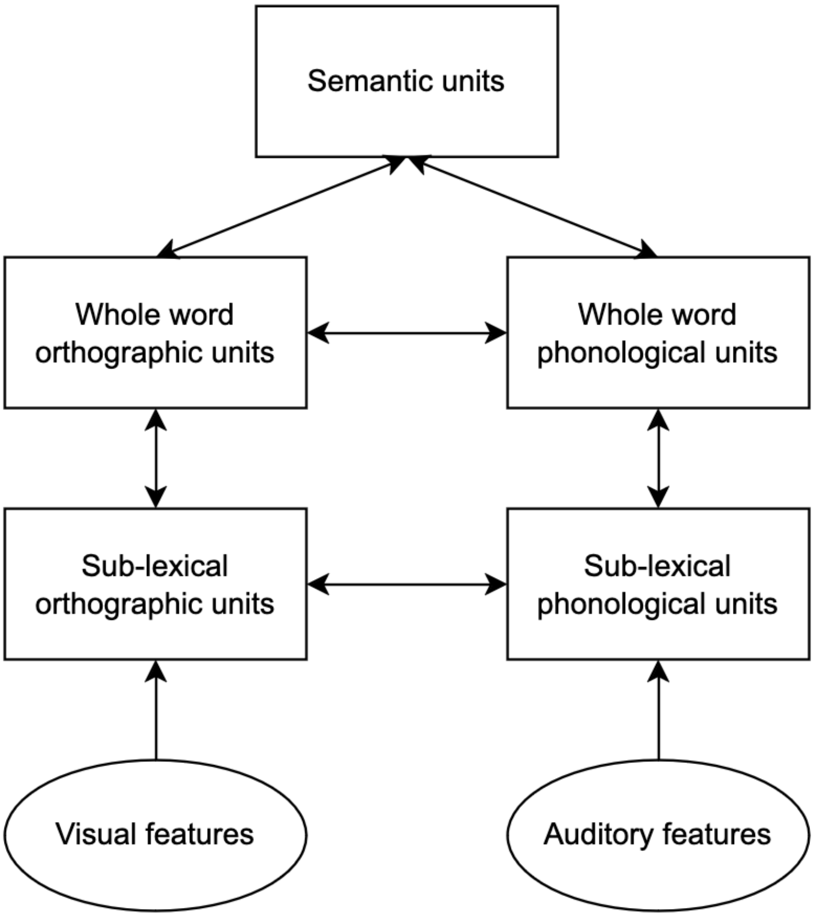
1.1.4 Bimodal Interactive Activation Model (BIAM)

In 1994, Grainger and Ferrand conducted experiments on orthographic priming in an effort to solve heterogeneous findings in the literature. It had been found that orthographic overlap between a prime and a target sometimes produced facilitative and other times inhibitory effects (Ferrand & Grainger, 1992; Segui & Grainger, 1990). In their first experiment, they presented participants visually with targets preceded by homophone primes in French. Homophones could either be orthographic neighbors (e.g., *fois* 'times' – *foie* 'liver', both pronounced /fwa/) or they were not orthographically related (e.g., *sans* 'without' – *cent* 'hundred', both pronounced /sɑ̃/). Primes were of higher frequency than target words. The assumption of the authors was that a high-frequency prime should inhibit the subsequent target word when prime and target were orthographically related due to lateral lexical inhibition (see also Segui & Grainger, 1990). The activation of an orthographic word form in the mental lexicon leads to the inhibition of orthographically similar word forms in order to enable the access to the correct word candidate and avoid interference from other words. High frequency words will be preferentially activated (via a lower activation threshold) because they have a higher probability of being the correct candidate. However, the authors observed the exact opposite pattern: Homophone primes reduced reaction times to targets in a lexical decision task when the prime was of higher frequency. This effect was significantly stronger when prime and target were orthographically similar compared to when they were orthographically dissimilar. In a second experiment, they introduced a condition of orthographically similar non-homophonic words pairs (e.g., *chat* /ʃa/ - *char* /ʃaʁ/), where the prime was of higher frequency than the target. In accordance with the findings reported by Segui and Grainger (1990), they found inhibitory effects for higher frequency primes on lower frequency targets for non-homophonic orthographic neighbors. However, when the orthographically related pairs were homophones, the priming effect was facilitative in nature.

These results can only be explained when both modalities are taken into account simultaneously: The facilitation of a higher frequency orthographically similar prime on target processing must stem from the phonological overlap between prime and target. Therefore, taking the Interactive Activation Model (IAM; McClelland & Rumelhart, 1981) as the basis, Grainger and Ferrand (1994) propose an extension of the model to include phonological representations. The IAM explains visual word recognition solely based on orthographic representations: Letter features activate related letters which feed activation forward to words containing these letters. Bidirectional excitatory and inhibitory connections between the letter and the word level are implemented in the model. Thus, activated letters inhibit words that do not contain these letters and excite words that do contain them. Likewise, activated words excite letters that are compatible with them (between-level excitation/inhibition). At the same time, activated letters inhibit other letters and activated words inhibit other words competing for identification (within-level inhibition). However, because the orthographic overlap between homophonic and non-homophonic word pairs in the studies by Grainger and Ferrand (1994) was identical, the IAM cannot explain the contradictory results. Consequently, the authors implemented a bimodal extension of the IAM, the Bimodal Interactive Activation Model that has since been revised (BIAM; Grainger & Ferrand, 1994, 1996; Grainger, et al., 2003; Grainger & Holcomb, 2009; Ziegler, Muneaux & Grainger, 2003).

Figure 2

Basic architecture of the Bimodal Interactive Activation Model



Note. Adapted from Grainger and Ferrand (1994).

The basic architecture of the BIAM is presented in Figure 2. The BIAM assumes representations on sub-lexical (graphemes, phonemes) and lexical (orthographic and phonological whole words) levels. Bidirectional links between orthography and phonology are implemented on both levels of processing. When a written word form is encountered, visual features activate letters which in turn activate sub-lexical orthographic representations. The activated sub-lexical orthographic representations feed activation forward in two ways: to whole word orthographic representations which contain the activated graphemes and to corresponding sub-lexical phonological representations. The activated whole word orthographic representations and the sub-lexical phonological representations both activate whole word phonological units. Lexical representations of both modalities are connected to semantic meaning. The BIAM was originally designed to model visual word recognition, but the architecture also allows inferences for the bimodal processing of spoken words: articulatory features extracted from the speech signal activate sub-lexical phonological units that automatically and directly communicate with sub-lexical orthographic units. The sub-lexical units in turn activate the corresponding whole-word orthographic and phonological representations, which connect to the semantic meanings (Grainger & Holcomb, 2009; Perre et al., 2009).

Because the BIAM assumes that upon encountering a word in either modality, both orthographic and phonological representations are automatically activated on a sub-lexical and lexical level, it is in line with the findings on bimodal word recognition reported in the previous sections. The fast and automatic activation of phonology in reading is explained by the transmission of activation to sub-lexical and lexical phonological representations, which explains homophone and pseudohomophone effects in visual word recognition. Likewise, effects of spelling inconsistencies, orthographic overlap and pseudohomograph priming in spoken word recognition can be explained on the basis of a fast and automatic activation of orthographic representations by corresponding phonological units. Furthermore, the BIAM represents a co-activation account: Bimodal word processing is enabled by a joint activation of orthographic and phonological units rather than a restructuring of phonological representations.

In conclusion, this section has provided evidence that the acquisition of an orthographic system leads to a dynamic mental lexicon that enables consistent interaction between the phonological and orthographic systems. In light of the reviewed evidence, the assumption of the phonological system as the core structure for language processing while orthography is merely a secondary, appended system cannot be upheld. Extensive findings show that orthography is involved in a rapid and automatic manner in spoken word recognition in the same way as phonology is involved in visual word recognition. This makes word processing a bimodal process, irrespective of the input modality. The bimodal processing of words is enabled by a joint activation of phonological and orthographic representations in the mental lexicon via bidirectional links between sub-lexical and lexical orthography and phonology as implemented in the BIAM.

However, when reviewing the evidence presented so far, it is very striking to note that almost all of the available studies have been conducted in English or French. To my knowledge, only two studies exist to date that have investigated the bimodal processing of orthography and phonology in other languages. Frost and Katz (1989) simultaneously presented spoken and written words in a same/different task to English and Serbo-Croatian participants. Ventura et al. (2004) conducted an experiment on the orthographic consistency effect in Portuguese. Both studies found diminished effects of bimodal processing for Serbo-Croatian and Portuguese compared to English and French, respectively, and attribute these findings to the orthographic depth of the languages (Frost & Katz, 1989; Pattamadilok, Morais et al., 2007; Ventura et al., 2004). This indicates that bimodal word processing is modulated by orthographic depth and might not generalize in the same way to languages other than English and French.

1.2 The concept of orthographic depth

> Orthographic depth is relevant for a broad range of issues, including reading development, developmental and acquired reading disorders, and theoretical accounts of reading. All aspects of reading are intrinsically linked to the characteristics of the orthography, therefore establishing what orthographic characteristics affect reading processes, and the cognitive mechanisms via which this occurs, is important for practical and theoretical reasons. (Schmalz et al., 2015, p. 1614)

In 1985 Uta Frith arguably transformed the way linguistics and psychology thought about reading acquisition. She proposed three stages that children in alphabetic languages pass through to become proficient readers. But only five years later Wimmer and Hummer (1990) showed that the stages proposed by Frith based on observations of English-speaking children, most importantly the ‘logographic phase’, do not apply in the same manner to German children, because “the German writing system, in contrast to the English one, is phonologically rather transparent” (Wimmer & Hummer, 1990, p. 349). Ever since then has “phonological transparency”, or orthographic depth, been central in the investigation of reading and reading-related behaviors. The importance to consider the relative characteristics of a writing system when investigating its acquisition is intuitively clear. However, as has been shown in research in the last decades, orthographic depth has wide-ranging consequences not only for reading acquisition, but also for reading impairments such as dyslexia, reading performance in skilled readers as well as theoretical accounts of reading and has been the core concept to explain differences in reading-related behaviors across different languages (e.g., Goswami, 2010; Landerl et al., 1997; Rau et al., 2015; Schmalz et al., 2015; Seymour et al., 2003; Wimmer & Goswami, 1994; Ziegler & Goswami, 2005).

In the following section, I will establish what the term ‘orthographic depth’ means within this thesis and why it is important to consider orthographic depth not only when investigating reading per se, but also when looking into the interplay of orthographic and phonological information during spoken word processing. When treating orthographic depth as an environmental factor for orthographic and phonological processing, it is paramount to clearly define the concept one is referring to. Therefore, I will start out with reviewing definitions of orthographic depth and further break down the concept into two relevant components:

complexity and consistency. Following this, I will discuss how orthographic depth can be measured and how these measures categorize different orthographic writing systems along the dimension of orthographic depth. Then, I will establish the difference between feedforward and feedback consistency and relate these concepts to orthographic depth. Finally, I will show that orthographic depth, though being a theoretical and abstract construct, has a neurobiological reality that I take as the basis for my own investigations into the significance of orthographic depth on the on-line processing of orthographic and phonological information during spoken word recognition.

1.2.1 Definitions of orthographic depth

In a very general sense, orthographic depth can be defined as the "reliability of print-to-speech correspondences" (Schmalz et al., 2015, p. 1614). Orthographies are considered deep if their mapping between graphemes and phonemes is unreliable because the same grapheme can have multiple pronunciations. English is considered a deep orthography because it has a many-to-many-mapping of graphemes to phonemes, so that grapheme-phoneme-correspondences are often intransparent (Goswami et al., 1997; Richlan, 2014). Consider for example the grapheme <ough> that can have a myriad of different pronunciations, such as /uː/ as in 'through', /oʊ/ as in 'though', /ʌf/ as in 'tough', /ɔf/ as in 'cough', /aʊ/ as in 'bough' or /ʌp/ as in 'hiccough'. Thus, the pronunciation of the grapheme is not readily available. Contrarily, a language is considered shallow if the mapping between graphemes and phonemes is reliable and transparent. German is generally considered a very transparent orthography, especially compared to English (e.g., Schmalz et al., 2015; Seymour et al., 2003; Wimmer, 1996; Wimmer & Goswami, 1994), because the same grapheme is usually pronounced in only one or at least only in very few different ways. For example, the grapheme <a> in the German words 'Bank', 'Ball' and 'Park' is always pronounced in the same way, namely /a/, while the same grapheme in the corresponding English words 'bank', 'ball' and 'park' is always pronounced differently: /æ/, /ɔː/ and /ɑ/, respectively. Consequently, German comes close to a one-to-one-mapping between graphemes and phonemes, meaning that each grapheme is only connected to one possible pronunciation (Goswami et al., 1997). However, a complete one-to-one-mapping of graphemes to phonemes is hardly ever achieved and even highly transparent languages can have albeit rare inconsistencies in grapheme-to-phoneme mappings. For example, the German grapheme <e> is connected to the three different phonemes /e:/ as in 'Steg' (engl. footbridge), /ɛ/ as in 'Zelt' (engl. tent) and /ə/[1] as in 'Lampe' (engl. lamp).

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[1] Note that the status of /ə/ as a phoneme of German is being debated in the literature (e.g., Wiese, 2000).

The term ‘orthographic depth’ has originally been used to describe two different types of correspondences because orthographies follow two basic principles: the phonological principle that one grapheme should correspond to one phoneme and the morphological principle that morphemes should be spelled consistently (Chomsky & Halle, 1968; Landerl & Reitsma, 2005). As such, the ‘depth’ of a writing system can refer to phonological or morphological transparency. An orthography can either reflect the pronunciation of the word and thus, exhibit a high degree of phonological transparency or it can reflect the morphology of the word, but usually not both. An exception is a language in which all morphological variants are pronounced in the same way. This way phonological and morphological transparency can both be retained in the orthography (Chomsky & Halle, 1968; Katz & Frost, 1992). For English, however, a high number of grapheme-phoneme-inconsistences stem from the fact that the morphological units of the words are retained in the spelling.

For example, the spelling of the words ‘heal’ and ‘health’ does not reflect the words’ pronunciations but rather their semantic relatedness. Therefore, in the English orthography, grapheme-phoneme-correspondences are often discarded in favor of reflecting morphological transparency. Contrarily, the spellings of the Dutch words ‘lezen’ (to read) and ‘[ik] lees’ ([I] read) follow the different phonological patterns observed in spoken language but omit the morphological relatedness between the words. Therefore, Dutch displays transparent grapheme-phoneme-correspondences while being morphologically intransparent (Landerl & Reitsma, 2005; Schmalz et al., 2015). In the reading literature, phonological transparency has received far more attention than morphological transparency, thus that the term ‘orthographic depth’ is usually used to refer to the concept of phonological transparency. Consequently, for the remainder of this thesis, I will use ‘orthographic depth’ to refer to the reliability of grapheme-phoneme-correspondences[2] reflected in a writing system.

Not only does orthographic depth affect a broad range of reading-related behaviors, but it also influences the representational units of orthography and phonology reflected in the mental lexicon. In their Psycholinguistic Grain Size Theory (PGST), Ziegler and Goswami (2005) propose that reading acquisition faces, among other challenges, the “granularity problem”. The inconsistencies in a language affect different orthographic units in a different way. In inconsistent orthographic systems, the larger the orthographic unit, the more consistent the spelling-to-sound-mapping. For example, in English, inconsistencies most prominently affect grapheme-to-phoneme correspondences. It might, therefore, be more feasible for English readers to connect orthographic and phonological representations at a higher level. For some

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[2] For discussion of phoneme-grapheme-correspondences see 1.2.3 of this thesis.

words, rimes can be suitable units to code the phonological information. Take the grapheme <ea> for example. This grapheme is pronounced /ɛ/ in the word 'bread', but /iː/ in the word 'beak'. The rimes '-ead' and '-eak', however, are more consistent in their spelling-to-sound mapping (e.g., '-ead' is always /ɛd/ in 'head', 'stead', 'thread', 'dread', 'lead', etc. and '-eak' is always /i:k/ in 'peak', 'leak', 'wreak', 'speak', 'weak', etc.).

However, consider that the rime '-eak' can also be pronounced /eɪk/ as in 'break'. Thus, inconsistencies can exist at both the grapheme level and the level of bodies (Schmalz et al., 2015) and the unit of the rime might not provide sufficient information to derive the correct pronunciation. Because of this, for other English words, only the whole-word-level orthographic form provides enough information to know how to pronounce a certain grapheme or body. For example, the grapheme <ai> in the words 'said' (/sɛd/) and 'paid' (/peɪd/) can only be correctly pronounced once whole-word unit information becomes available. Consequently, Ziegler and Goswami (2005) propose that readers in deep orthographies develop correspondences between orthography and phonology on multiple levels of orthographic units. Because there are more rimes than graphemes and more whole words than rimes, the number of correspondences that need to be learned is higher in deep orthographies than in shallow orthographies. This is taken as one reason why reading development takes longer for readers in deep orthographies compared to readers in shallow orthographies.

In shallow orthographies, the consistency between graphemes and phonemes is higher, so that correspondences between orthographic and phonological units can take place at a lower level, such as the grapheme-phoneme level. Consequently, the number of correspondences that need to be learned is lower in shallow orthographies, making the reading task easier for developing readers. Studies, indeed, have found that rime analogy is a strategy that is used more in deep languages such as English and French than in shallow orthographies such as Spanish or Greek (Goswami et al., 1997, 1998). Goswami and colleagues (1997) presented 7-, 8- and 9-year-old children with pseudowords that varied in their orthographic familiarity on the rime level. They compared O+P+ bisyllabic and trisyllabic pseudowords that contained orthographically familiar rimes (e.g., *bomic* derived from 'comic') to O-P+ pseudowords that contained orthographically unfamiliar rimes (e.g., *bommick* derived from 'comic').

While familiar orthographic patterns allow the derivation of phonology from higher-level orthographic units, in this case rimes, unfamiliar orthographic patterns need to be read based on grapheme-phoneme-correspondences. The authors found that reading performance in the two conditions differed much more for English readers than for Greek readers, indicating that orthographic familiarity at the rime level plays a much more important role in a deep orthography than in a shallow orthography. This finding was replicated by Goswami et al. (1998) comparing English, French and Spanish. They found facilitatory effects of orthographic familiarity of the rime in all three languages, but the size of the effect was larger the deeper the orthography was, with highest effects found in English, somewhat reduced effects in French and smallest effects in Spanish. Their results also provide evidence that reading performance in shallow orthographies is quite high even in young readers, while reading accuracy and speed in deep orthographies need more time to develop in agreement with predictions of the PGST.

Even though these examples give an idea of how 'deep' and 'shallow' orthographies differ and how this relates to differences in cross-linguistic reading behaviors and orthographic-phonological-representations, it does not yet establish the exact characteristics of the writing systems that make it 'deep' or 'shallow'. Katz and Frost (1992, p. 71) suggest that "[…] shallow orthographies have relatively simple, consistent, and complete connections between letter and phoneme […]". From this statement, we take that orthographic depth is not a unitary construct, but is comprised of three different components: complexity, consistency, and completeness. The authors make the case that shallow orthographies rely more on sub-lexical activation of phonological information, because sub-lexical units (e.g., graphemes) provide enough information about a word's pronunciation so that the sub-lexical phonology is more readily available in shallow orthographies and will more likely be used for both pronunciation and lexical access. Consequently, assembled phonology should play a greater role in shallow than in deep orthographies. This is referred to as the Orthographic Depth Hypothesis (ODH) and explains the mechanisms behind language-specific differences in reading performance. Note that this is in line with the PGST described above: the more inconsistencies at the grapheme-phoneme-level the more likely the reliance on larger orthographic units.

The ODH has influenced currently used models of reading that propose two different routes that can be used to derive phonology from orthography. I will use the Dual-Route Cascaded Model (DRC; Coltheart et al., 2001) introduced in previous sections of this thesis as an example. This model assumes that printed words activate visual feature units and letter units that correspond to these visual features. Then the model proposes two different routes that are simultaneously activated: a non-lexical route that derives phonology from the activated letters via grapheme-phoneme-correspondence rules and a lexical route that is based on an orthographic lexicon in which words that contain the activated letters are activated in their whole-word form and are then connected to the word's pronunciation. Based on the ODH we can assume that the non-lexical route plays a greater role in shallow orthographies than in deep orthographies and vice versa. Again, this is in line with the PGST: The reliance on the non-lexical route will be less successful if grapheme-to-phoneme correspondences are unreliable. Readers in deep orthographies will more often read via the lexical route, because only whole-word orthography provides enough information to access the correct phonological word form. In shallow orthographies, on the other hand, relying on the non-lexical route will prove successful in most cases. This has important consequences for reading acquisition and pseudoword reading (Landerl, 2000; Seymour et al., 2003; Wimmer & Goswami, 1994): The acquisition of an orthographic lexicon is rather straightforward in a shallow orthography, because once grapheme-phoneme-correspondences are established, beginning readers can build an orthographic lexicon based on the limited number of grapheme-phoneme-relations. Contrarily, readers in deep orthographies have to rely on body or whole-word units to establish an orthographic lexicon, which will take longer. Reading of pseudowords will also be more successful in shallow orthographies than in deep orthographies, especially if it relies on small units as shown above in the studies by Goswami et al. (1997, 1998).

There are two reasons why grapheme-phoneme-correspondences are unreliable and, consequently, why the lexical route will be more involved in reading: the complexity and (in)consistency of grapheme-phoneme-correspondences. Complexity refers to the set of rules that relate graphemes to phonemes. The rules that are applied by the non-lexical route can be simple or complex. Simple rules are grapheme-phoneme-correspondences that always apply when a grapheme is encountered. Complex rules are either context-sensitive rules that require more correspondences between graphemes and phonemes by taking surrounding letters and/or letter positions into account or they involve multi-letter graphemes. A simple grapheme-phoneme-correspondence rule is, for example, that the letter <g> is always pronounced /ɡ/, a context-sensitive rule is that the letter <g> is pronounced /ɡ/ before letters <a, o, u>, but /ʤ/ before the letters <e, i> as is the case in Italian. A rule is also complex if the grapheme involves more than one letters (e.g., <th> → /θ/). The more complex rules are required to comprehensively map graphemes onto phonemes, the higher the system's complexity. If a grapheme-phoneme-system relies on a wide number of complex rules, the non-lexical route will take longer, and it will become more likely that the lexical route is used to derive the correct phonology (Richlan, 2014; Schmalz et al., 2015).

Consistency, also referred to as 'transparency' (Richlan, 2014) or 'predictability' (Schmalz et al., 2015), reflects the likelihood with which the rules lead to the correct phonology. A system is consistent if the application of the rules reliably leads to the correct pronunciation and a system is inconsistent if the correct pronunciation cannot be derived even if the grapheme-phoneme-correspondence rules are followed. Consider, for example, the English words 'gift'

(/gɪft/) and ‘gist’ (/d͡ʒɪst/). Neither the application of a simple nor a context-sensitive rule is sufficient to derive the correct pronunciation of the letter /g/ in this case. Thus, the lexical route must be recruited to get from the orthographic to the corresponding phonological representation, because the sub-lexical information is not sufficient. The pronunciation of the word is not consistent with any rules that exist in the respective language and is consequently not predictable. The differentiation of complexity and consistency is important because a language that is complex, but highly consistent will likely have different processing demands than a language that is complex and inconsistent (Schmalz et al., 2015). In sum, the complexity and consistency of grapheme-phoneme-correspondences modulate the use of non-lexical and lexical information to derive phonology from orthography. The less complex and the more consistent an orthography, the higher the involvement of sub-lexical phonological information via the non-lexical route and the shallower an orthography.

Lastly, the component of completeness refers to the involvement of sentential context information in the derivation of the correct phonology. The lexical information is incomplete if the target phonological word form and the connected semantic meaning cannot be derived from the written word form alone. This is the case for heterophonic homographs, for example the English word ‘bow’. The pronunciation and meaning of the word differ depending on the context as in ‘a ship’s bow (/baʊ/)’ or ‘bow (/bəʊ/) and arrow’. In this case, even the whole-word orthographic form does not provide enough information to access the correct pronunciation and semantic representation. The context information provided by the phrase or sentence needs to be taken into account to establish the correct mapping of orthography onto phonology and semantics (Schmalz et al., 2015). The more heterophonic homographs a language possesses, the higher its incompleteness and the deeper the orthography. The component of completeness is important to predict reading performance and processing on levels above the word unit. For this thesis, processing on the word level is being focused such that the component of completeness will not be further examined.

To conclude, the previous sections have shown that the term ‘orthographic depth’ is used to refer to the phonological transparency of a writing system, that inconsistencies in the phonological transparency often stem from adherence to the morphological principle and that phonological transparency influences reading-related behaviors as well as the very representations of and connections between a language’s orthographic and phonological units in the mental lexicon. Finally, it has been established that orthographic depth can be divided into the components of complexity and consistency. I defined complexity as the number and nature (simple vs. complex) of grapheme-phoneme-correspondence rules that are necessary to comprehensively map orthography onto phonology. Consistency was defined as the likelihood with which the application of these rules leads to the correct phonology. An orthography is complex if many context-sensitive rules are required to map all graphemes onto phonemes or if it has a high number of multi-letter graphemes. An orthography is inconsistent if the application of these rules does not lead to the correct pronunciation of the word and, hence, if the pronunciation of the word is not predictable.

1.2.2 Measuring orthographic depth

Orthographic depth is a construct that is not directly observable but has to be operationalized, meaning that rules have to be defined by which the correlates of orthographic depth can be measured. In the previous section, I have broken down orthographic depth into the components of complexity and consistency. Complexity relates to the number and nature of rules for grapheme-phoneme-correspondences, while consistency corresponds to the likelihood that the application of these rules will lead to the correct phonological form. In order to localize orthographies on the continuum of orthographic depth, the relative degree of complexity and consistency of each writing system must be quantified. Different approaches have been taken in the literature to manage this task and these different measures arrive at different outcomes. In the following, I will review the different measures and discuss their advantages and disadvantages before presenting the approach I rely on for this thesis to localize English and German, the two languages under investigation in my studies, on the dimension of orthographic depth.

Ideally, approaches to measuring orthographic depth should be objective and replicable. Irrespective of the person measuring the orthographic depth of a specific writing system, the result should always be the same and measuring the same writing system multiple times with the same measure should always lead to the same result. However, one approach taken in the literature to “measure” orthographic depth is the subjective judgment of experts. Seymour et al. (2003) investigated how orthographic depth influences the acquisition of basic decoding skills by assessing letter knowledge, familiar word reading, and simple nonword reading in English and 12 other European orthographies that vary in orthographic depth. Deep orthographies are defined by the authors as those that contain orthographic inconsistencies and complexities, such as multi-letter graphemes, context-dependent rules, irregularities, and morphological effects. Shallow orthographies are defined as those that approximate a one-to-one-mapping between letters and phonemes. In these definitions, we find the relevant components of orthographic depth I have established in the previous section. However, it also becomes clear that these have not been distinguished in the approach used by Seymour et al. (2003) and are, thus, confounded in the expert estimations of orthographic depth in their study. Moreover, it is not clearly stated how the researchers were instructed to judge the orthographic depth of 'their' writing system, i.e., which characteristics to consider and how to weigh them against each other. The authors merely describe that researchers from 16 different European countries collaborated to review characteristics that are likely to influence reading acquisition, namely syllabic complexity, and orthographic depth, and gave an "intuitive estimate" (Seymour et al., 2003, p.167).

The authors provide a "hypothetical classification" of the languages under investigation regarding these two characteristics. This classification is shown in Table 1. As can be seen, the dimension of syllabic complexity mostly differentiates between the Romance and the Germanic languages. The first have a predominance of consonant-vowel syllables, while the latter show consonant-vowel-consonant syllables with complex consonant clusters in onset and coda positions (Seymour et al., 2003). With regards to orthographic depth, German has been estimated to be rather shallow, while English is considered to be exceptionally deep, having been put at the very end of the depth spectrum. French and Portuguese as well as Dutch, Swedish and Danish have been put in between German and English and have, thus, been found to be of intermediate depth.

Table 1

Hypothetical classification of syllabic complexity and orthographic depth of European languages as provided by Seymour et al. (2003)

		Orthographic depth				
		Shallow				**Deep**
Syllabic structure	**Simple**	Finnish	Greek Italian Spanish	Portuguese	French	
	Complex		**German** Norwegian Icelandic	Dutch Swedish	Danish	**English**

The authors find some indication that letter knowledge, familiar word reading, and simple nonword reading are influenced by differences in orthographic depth as judged by the researchers. Though, variance in letter-sound knowledge could not be attributed to either syllabic complexity or orthographic depth, both accuracy and speed of reading familiar words significantly varied with the latter. For both simple and complex syllabic languages, accuracy and speed were significantly lower in deep than in shallow languages with English showing the lowest values followed by French, Portuguese and Danish, which were below all other languages. Similar results were found for simple non-word reading. Here, however, an effect of syllabic complexity was also established, showing that non-word reading was easier in languages with simple syllabic structures. The authors also show that learning to read is harder, i.e., more time is needed to develop reading competency, in deep orthographies such as Portuguese, French and English, a finding that is well established in the literature (e.g., Landerl, 2000; Goswami et al., 1997, 1998; Wimmer & Goswami, 1994; Ziegler & Goswami, 2005). As such, the subjective ratings given by the research consortium seem to have some merit.

However, the authors also point out that French and Portuguese behave differently than the other simple syllabic languages and English behaves differently than the rest of the complex syllabic languages. The authors give no explanation for this finding. As will be shown below, one reason for this result can be found in the confounding of complexity and consistency in the study by Seymour et al. (2003). Moreover, as pointed out above, the approach used by the authors is subjective and it remains unclear how the researchers were instructed, which makes it impossible to reconstruct the estimation process. Some variability in the languages investigated by the authors could neither be attributed to syllabic complexity nor to orthographic depth, indicating that other factors might have been at play that have not been controlled by the authors. Again, the differentiation of complexity and consistency could have contributed to distinguishing sources of variability between the languages and could, thus, be an explanation for at least some of the unexplained variance.

Other approaches towards measuring orthographic depth rely on more objective and replicable measures. One such approach is the calculation of onset entropy. Onset entropy refers to the ambiguity of word-initial letter-to-phoneme-correspondences. If the first letter in a word always corresponds to the same phoneme, its entropy will be zero. However, if the word-initial letter has more than one possible pronunciation, the entropy will increase with the number of phonemes connected to the grapheme. Consequently, onset entropy values are the quantification of the idea of a one-to-x-mapping of graphemes onto phonemes. However, the onset entropy not only takes into account the number of phonemes connected to the first grapheme, but also the frequency of occurrence of a grapheme-phoneme-correspondence. If two phonemes are connected to the word-initial grapheme, but one of these correspondences is very rare, then the onset entropy will not be much higher than the entropy value for an unambiguous grapheme that only has one possible pronunciation. However, if the word-initial grapheme can be pronounced in two different ways with the same frequency, then the onset entropy will be higher. Thus, rare pronunciations are only marginally reflected in the onset entropy values (Borgwaldt et al., 2004, 2005).

High entropy values can occur for three different reasons: The involvement of the word-initial letter in multi-letter graphemes (e.g., <p> in <ph> as in 'photograph') will increase the entropy value. Secondly, the existence of context-sensitive grapheme-phoneme-rules involving the word-initial grapheme will lead to a higher number of connected possible pronunciations. Lastly, what Borgwaldt and colleagues (2005, p. 215) call the "true letter-to-phoneme ambiguity" refers to the correspondence of one grapheme to more than one phoneme irrespective of the involvement in multi-letter graphemes and context-sensitive rules and will also increase the entropy value (e.g., the German word-initial letter <v> that can be pronounced /f/ as in 'Vater' (engl. father) or /v/ in 'Vase' (engl. vase)). It should be apparent that the first two cases relate to the component of complexity while the last case corresponds to consistency as defined in the previous section. Therefore, onset entropy values again confound the two components of orthographic depth. The concept of complexity as I defined it in the previous section, only considers the number of rules, not their frequency of appliance. For the non-lexical route as proposed by the DRC model, only the number of rules in the grapheme-phoneme-correspondences, but not their frequency is considered. Thus, the onset entropy defines complexity differently and attributes less complexity to an orthography with many, but rare grapheme-phoneme-correspondence rules relative to an orthography with less rules, that are applied equally as often. To my knowledge, it is unclear how the frequency of grapheme-phoneme-rules influence reading and reading-related behaviors.

Borgwaldt and colleagues (2004) calculated the onset entropy of word forms for the following European languages: Dutch, English, French, German, and Hungarian. The authors report the relative deviance from a one-to-one-mapping of the first letter onto the corresponding phoneme(s) as shown in Table 2. The higher the deviance value the further the orthography is from a one-to-one-mapping of the first letter onto the first phoneme. As can be seen, none of the languages show a deviance value of 0.00, which corresponds to a one-to-one-mapping. Based on the initial-letter entropy value, Hungarian has the shallowest orthography, followed by Dutch. Interestingly, according to this measure of orthographic depth, French is shallower than German, though both have almost identical values. English, again, is the deepest of the investigated orthographies. For German in particular, this finding contradicts the expert judgments of Seymour et al.'s (2003) study, where German was estimated to be shallower than Dutch and French. One reason for this contradictory finding can be seen in the fact that French inconsistencies are often found in the coda position, not at the onset of the word (Schmalz et al., 2015). Thus, by only taking word-onset into account, the values might be biased. As has been described above, German shows a complex syllabic structure in onset positions which might lead to higher complexity when only the word-initial letter is taken into account due to involvement in multi-letter graphemes such as <sch> (/ʃ/) or <st> (/ʃt/) which might drive the relatively high onset entropy for German.

Table 2

Deviance from a one-to-one-mapping of the first letter onto the first phoneme for five languages as reported by Borgwaldt et al. (2004)

Language	Hungarian	Dutch	French	German	English
Deviance	0.13	0.24	0.42	0.43	0.52

Note. Values are approximate values as the exact values are not reported by the authors and are only depicted graphically.

Borgwaldt et al. (2005) measured onset entropy based on the lemma rather than the word forms of the languages Dutch, English, French, German, Hungarian, Italian, and Portuguese. They found highest entropy values for English followed by French, German, Portuguese, Dutch, Italian and Hungarian. Again, English is found to be the deepest of the investigated orthographies. Based on lemma onset entropy, French was estimated to be deeper than German, however, the values were again very close to each other. In sum, based on onset entropy values, German must be considered shallower than English, however, the results rather speak for German as a deep orthography in comparison with other European languages. This is in marked contrast with the estimation of Seymour et al. (2003). While restricting analyses to word-initial letters allows the inclusion of mono- and polysyllabic words in the calculations, the results don't take into account that inconsistencies in grapheme-phoneme-correspondences don't follow the same word-internal distribution in all orthographies. German might have higher complexity in the word-onsets due to involvement of letters in multi-letter graphemes, while inconsistencies in French are more prone to appear in the coda position (Schmalz et al., 2015). Moreover, the onset entropy measure confounds complexity and consistency and defines complexity not only as the number of grapheme-phoneme-correspondence rules, but also their frequency. This might set this measure apart from other measures of orthographic depth.

Van den Bosch and colleagues (1994) propose two different measures of orthographic depth that are calculated from text corpora based on computational algorithms. Grapheme-to-phoneme conversion or graphemic parsing is related to the concept of complexity and is used to establish how difficult it is to parse letter strings into graphemes. Parsing accuracy will be high, if graphemes correspond only to one letter, because parsing a word into single letters will enable the correct mapping from graphemes onto phonemes. For example, an English word like ‘cat’ can simply be parsed into <c>, <a> and <t>, which can directly be mapped onto the corresponding phonemes /k/, / æ/, and /t/. However, the word ‘chair’ is much more difficult to parse because the correct parsing <ch> and <air> involves complex rules (Schmalz et al., 2015). Consequently, parsing accuracy will be lower, i.e., it will be harder to parse a letter string into graphemes, if an orthography has either a high number of multi-letter graphemes or if grapheme-phoneme-correspondences are restricted by context-sensitive rules (Schmalz et al., 2015; van den Bosch et al., 1994). The second measure is called generalization performance and corresponds to the component of consistency. Generalization performance describes the accuracy with which the application of grapheme-phoneme-correspondences leads to the correct “reading” of new words. Firstly, a learning algorithm extracts grapheme-phoneme-correspondences including multi-letter graphemes and context-sensitive rules from a training set, then a second, search algorithm maps new graphemic input strings onto the appropriate phonemes. Generalization performance will be high if the application of grapheme-phoneme-correspondence rules reliably leads to the correct mapping, i.e., if the orthography is consistent (van den Bosch et al., 1994). Table 3 demonstrates the performance accuracies for three different orthographies: English, French and Dutch.

Table 3

Computationally extracted graphemic parsing and generalization performance based on English, Dutch and French corpora as reported by van den Bosch et al. (1994)

Language	English	French	Dutch
Graphemic parsing accuracy	24.5%	12.9%	21.3%
Generalization performance accuracy	54.3%	89.1%	81.4%

Note. Parsing accuracy corresponds to correctly parsed letter strings of the full test set after training of 5,000 training partitions (van den Bosch et al., 1994). Generalization performance corresponds to correctly mapped whole words.

Table 3 shows that for graphemic parsing accuracy, English shows the highest performance value followed by Dutch, both of which outperform French by far. As stated above, parsing letter strings into graphemes will be easier if graphemes correspond to a single letter. Thus, a high number of multi-letter graphemes and/or context-sensitive rules will lead to worse performance of the parsing algorithm (van den Bosch et al., 1994). Thus, this can be taken as evidence that French shows a high degree of complexity, higher than that of Dutch or English. The fact that accuracy values are low for all of the investigated languages with none of them reaching 25% accuracy indicates that all of these orthographies show a rather high degree of complexity. Contrarily, generalization performance was highest for French followed by Dutch, both of which outperformed English. For French, 89.1% of whole words could be correctly mapped onto the corresponding phonemic word form based on grapheme-phoneme-correspondences. For English, the algorithm only reached 54.3% accuracy indicating that English shows a high number of words that cannot be accurately mapped based on grapheme-phoneme-correspondences. Thus, English shows a high degree of inconsistency, while French can be seen as a consistent orthography.

This measure of orthographic depth is, thus, the first that distinguishes between the components of complexity and consistency and shows that English is both very complex and very inconsistent, while French is even more complex than English, but shows a high degree of consistency. Consequently, English can be considered a deep orthography on both of these components. However, French and Dutch are complex, but consistent languages. Taking this into consideration sheds a new light onto the results of Seymour et al. (2003) and Borgwaldt et al. (2004, 2005): If complexity and consistency are not distinguished, French is estimated as being of intermediate depth both with respect to intuitive ratings as well as based on entropy values. Thus, differentiating between these two components can explain why results for French cannot easily be compared to other languages as it seems to be exceptionally complex and exceptionally consistent at the same time. This might explain contradictory findings in the literature. Unfortunately, the study by van den Bosch et al. (1994) did not investigate German.

However, reverting back to the DRC model, comparing performances of the model across languages can give information about their complexity and consistency. As described in the previous sections, the DRC model proposes a non-lexical route that applies grapheme-phoneme-correspondences to derive phonology from activated letters and a lexical route that is based on an orthographic lexicon linking whole-word orthographic forms to whole-word phonological forms. Comparing the number of simple and complex rules of the non-lexical route across languages gives an indication of complexity of different orthographic systems. Taking the number of word forms into account that cannot be read correctly based on the non-lexical route, i.e., ‘irregular words’, provides an estimate of consistency across languages. This is exactly what Schmalz and colleagues (2015) have done based on DRC models of five different languages: Dutch, English (Coltheart et al., 2001), French (Ziegler, Perry & Coltheart, 2003), German (Ziegler et al., 2000) and Italian. Table 4 shows the results of the comparison.

Table 4

Measures of complexity and consistency for Dutch, English, French, German, and Italian based on the respective DRCs as reported by Schmalz et al. (2015)

Language	Dutch	English	French	German	Italian
Total number of rules	104	226	340	130	59
Single-letter rules	51 (49.0%)	38 (16.9%)	46 (13.5%)	44 (33.8%)	19 (32.2%)
Multi-letter rules	42 (40.4%)	161 (71.2%)	218 (64.1%)	55 (42.3%)	8 (13.6%)
Context-sensitive rules	11 (10.6%)	27 (11.9%)	76 (22.4%)	31 (23.8%)	32 (54.2%)
Irregular words (%)	6.3	16.9	5.6	10.5	NA

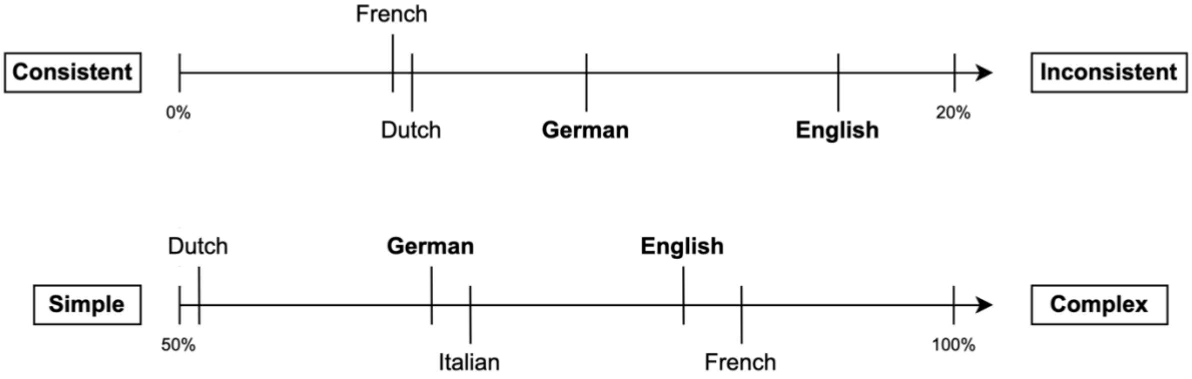
These results confirm the findings by van den Bosch et al. (1994) showing that French has by far the highest number of rules of all the languages investigated, followed by English. Looking at the nature of the rules, French and English both show a high amount of multi-letter and context-sensitive rules, thereby indicating a high complexity of both orthographic systems. Italian shows with 59 rules in total the least number of grapheme-phoneme-correspondence rules. This is followed by Dutch and German, which can both be characterized as being of medium complexity based on both the number and nature of the rules: They show an almost equal number of multi-letter and single-letter rules. Irregular words are those that cannot be pronounced based on the application of grapheme-phoneme-correspondence rules, hence, this number indicates an orthography's consistency. For Italian, this number is not indicated by Schmalz and colleagues (2015). It remains unclear as to why, because there should be at least some irregular words even in a very consistent orthography. Based on these results, French shows the lowest number of irregular word forms followed by Dutch, German and English. Thus, again, French is characterized as an extremely consistent orthography with an exceptionally high complexity, placing it on opposite ends of the orthographic depth spectrum. English shows the highest number of irregular words indicating its low consistency. Taken together, these results show that English is both complex and inconsistent while German can be seen as an orthography of medium complexity and consistency based on the results provided by Schmalz and colleagues (2015) and in comparison to the other languages under investigation.

Four different approaches to measuring orthographic depth have been reviewed in this section. Based on intuitive expert judgments carried out by Seymour et al. (2003), German has been estimated as a rather shallow orthography, while English was considered as the deepest of the orthographies under investigation. This estimate has been confirmed by measures of onset entropy, again showing that English shows the highest entropy values. Here, some contradictions have been found for German and French. While previously, German has been found to be quite shallow and French has been judged to be of intermediate depth, onset entropy values place both languages at similar points of the orthographic depth spectrum. I have suggested that one reason for this contradiction is that German onsets can be quite complex involving multi-letter graphemes, while French inconsistencies are often found in coda position.

Moreover, very critically, the definitions of orthographic depth the expert judgments and the onset entropy calculations have been based on, did not distinguish between complexity and consistency, leading to a confounding of the two components. The measures of graphemic parsing accuracy and generalization accuracy as well as the calculations based on cross-linguistic comparisons of DRC models both consider the two components of orthographic depth separately. The latter come to the conclusion that English shows both a high degree of complexity and a high degree of inconsistency. French, interestingly estimated as being of intermediate depth in the first two measures, has been shown to occupy a special position: It shows a higher complexity than English, but a higher consistency than German, occupying opposite ends of the complexity-consistency-spectrum. This spectrum is visualized in Figure 3. I based the consistency continuum on the percentage of irregular words and the complexity continuum on the percentage of complex rules as reported by Schmalz et al. (2015). German can be found in the medium range with regard to consistency but has a rather simple orthography. Thus, it shows considerably less complexity and inconsistency than English, but higher complexity and inconsistency than Dutch. For Italian, no consistency value has been given, however, Italian shows higher complexity than German in Figure 3, which is driven by the comparatively high number of context-sensitive rules for Italian. For the remainder of this thesis, I will refer to English as a deep orthography, meaning that it is both complex and inconsistent and I will refer to German as a shallow orthography in comparison to English, having a comparably simple and consistent orthography. However, it should be kept in mind that based on the results reported by Schmalz and colleagues, German scored medium levels in consistency relative to other languages such as French and Dutch.

Figure 3

Localization of English and German relative to French, Italian and Dutch on the complexity-consistency-spectrum



Note. Complexity is operationalized by the percentage of complex rules (multi-letter rules and context-sensitive rules) of total rules. Inconsistency is operationalized by the percentage of irregular words. Distances are based on percentage points. Values are taken from Schmalz et al. (2015). No value is reported for consistency of Italian.

So far, the definition of orthographic depth, its measures and the resulting findings have been limited and attributed to grapheme-phoneme-correspondences. This stems primarily from the rich literature on reading and reading-related behaviors that investigate how the reading system arrives from the orthographic word form to its corresponding phonological counterpart. It has, however, been suggested that phoneme-grapheme-correspondences also play a role in reading and might be even more important when investigating orthographic influences on spoken word recognition.

1.2.3 Feedforward and feedback consistency

Orthographic depth is usually defined based on the consistency and complexity of grapheme-phoneme-correspondences. However, phoneme-grapheme-correspondences might be different from the former, because one phoneme can be represented by more than one grapheme even if a grapheme only relates to one phoneme. Consider for example that in French, the letter <o> is always pronounced /o/, but the phoneme /o/ can be represented by multiple graphemes such as <o>, <au> or <eau> (Gimenes et al., 2020). Therefore, French can be described as very consistent from spelling to sound, but rather inconsistent from sound to spelling (Stone et al., 1997; Ziegler et al., 1996). Spelling-to-sound consistency is referred to as "feedforward consistency", while sound-to-spelling consistency is called "feedback consistency". In many shallow orthographies, there is an asymmetry between feedforward and feedback consistency. In German, grapheme-phoneme-correspondences are quite consistent, but phoneme-grapheme-correspondences are more inconsistent. Consequently, there are no words in German that have an identical spelling but are pronounced differently. However, words with the same pronunciation can have different spellings (for example, ger. ‘Wahl’ engl. election – ger. ‘Wal’ engl. whale, both pronounced [va:l]) (Görgen et al., 2021; Kargl et al. 2017; Moll et al., 2009).

A reason for the feedback inconsistency in German is morphological transparency. As discussed in section 1.2.1, morphological transparency is one of the two principles orthographies follow in their spelling. Many phonological inconsistencies can be explained by adherence to the morphological principle. For example, the singular form of the German word ‘Hund’ (engl. dog) is pronounced /hʊnt/ leading to a spelling inconsistency for the last phoneme /t/ that is spelled as <d>. However, when taking the plural form ‘Hunde’ (engl. dogs) into account, pronounced /hʊndə/, it becomes apparent that the inconsistency in the spelling has morphological reasons (Görgen et al., 2021). These inconsistencies influence the acquisition of spelling across languages because children first rely on phonological approaches in spelling before they acquire morphological strategies. Therefore, spelling acquisition should be easier for languages that adhere to phonological transparency in spelling as compared to morphological transparency. Consider for example the Dutch words ‘paar’ (engl. pair) and ‘paren’ (engl. pairs). The spelling strictly follows the phonological patterns of spoken language. Contrarily, the German corresponding words ‘Paar’ and ‘Paare’ follow morphological principles and are spelled consistently, even though the vowel /a:/ is related to three different graphemes (<a>, <aa>, <ah>). Just as is the case for feedforward consistency, languages that represent the morphological rather than the phonological structure are considered deep (Landerl & Reitsma, 2005).

Feedback consistency has received much less attention in the literature, even though some attempts have been made to raise awareness for the importance of considering sound-to-spelling-consistencies in the acquisition of written language. Stone and colleagues (1997) showed that not only feedforward, but also feedback consistency influences latencies in visual word recognition. The orthographic body <-eap> in the word ‘heap’ can only be pronounced in one way (/i:p/) as in ‘leap’, ‘cheap’, ‘reap’, etc., however, the phonological body /i:p/ can be spelled in different ways (e.g. <eap> or <eep> as in ‘deep’, ‘weep’, ‘keep’, etc.). As such, it shows high feedforward consistency, but feedback inconsistency. Contrarily, the orthographic body of the word ‘probe’ shows both feedforward and feedback consistency because it can only be pronounced /-oʊb/ and the phonological body /-oʊb/ can only be spelled <-obe> as in ‘lobe’, ‘globe’, etc. Stone et al. (1997) presented participants with words containing feedback inconsistent and feedback consistent bodies in a visual lexical decision task. Feedforward consistency was controlled. Participants responded significantly faster when the words contained feedback consistent bodies compared to words with feedback inconsistent bodies. Similar results for feedback consistency have been found in other tasks like naming and letter search tasks (Ziegler & Jacobs, 1995; Ziegler, Montant & Jacobs, 1997). Moreover, the effect of feedback consistency was found to have the same size than the effect of feedforward consistency in lexical decision (Ziegler, Montant & Jacobs, 1997). This demonstrates that feedback consistency plays an important role in the processing of orthographic information.

However, due to the relatively few studies investigating feedback consistency, systematic comparisons of feedback consistencies across languages are hard to find. For English, Stone et al. (1997) estimated that about 75% of all words contain feedback inconsistencies. Ziegler, Stone and Jacobs (1997) computed the feedforward and feedback consistency of English bodies based on a database containing 2,694 monosyllabic, monomorphemic words from Kučera and Francis (1997). They found that 69.3% of the investigated words contained bodies with feedforward inconsistencies and 72.3% contained bodies with feedback inconsistencies. As discussed in section 1.2.1 on the Psycholinguistic Grain Size Theory, inconsistencies in English are more pronounced for smaller units. Consequently, phoneme-to-grapheme-inconsistencies will be even higher than inconsistencies at the level of the body. Thus, English can be considered as very inconsistent in both spelling-to-sound and sound-to-spelling directions.

Using a similar method, Ziegler et al. (1996) computed feedforward and feedback consistency for French bodies based on 1,843 monosyllabic words taken from the BRULEX database (Content et al., 1990). They found that only 12.4% of the investigated words contained feedforward inconsistent bodies, but 79.1% of the words showed feedback inconsistencies. Therefore, the characterization of French as a highly consistent language as has been shown in the previous section, is only true for the spelling-to-sound, but not for the sound-to-spelling direction. A systematic investigation for German in a similar manner is currently lacking. However, using the same method as reported for the feedforward (spelling-to-sound) consistency described in the previous section, Borgwaldt and colleagues (2004) also calculated onset entropy values for the mapping of the first phoneme onto the first letter (sound-to-spelling) for the five languages Dutch, English, French, German, and Hungarian. They found that English, again, was the deepest orthography, followed by French, German, Dutch and Hungarian. Remarkably, relying on word-initial entropy, all languages showed higher deviance for grapheme-to-phoneme than for phoneme-to-grapheme inconsistencies, which is in contrast to the findings described above. Again, one reason might be that spelling inconsistencies appear not at the word onset, but in nucleus or coda position. Nonetheless, this implies that German feedback consistency is higher than English feedback consistency.

Landerl et al. (2013) categorize English, French, German, Dutch, Finnish and Hungarian into three categories of low, middle and high orthographic depth[3] based on both feedforward and feedback consistency. They categorize both English and French as deep orthographies, while Dutch and German are considered medium deep and Hungarian and Finnish are considered shallow orthographies. However, they describe that French shows “low feedforward and feedback consistency” (Landerl et al., 2013, p. 688), which clearly contradicts the findings regarding the consistency of French grapheme-to-phoneme-correspondences described in the previous section and reported above by Ziegler et al. (1996). Landerl and colleagues (2013) are highly influenced by Seymour et al. (2003) and Borgwaldt et al. (2005), which might explain the contradictory findings for French and shows again the importance of a clear definition of the concepts and a distinction between complexity and consistency.

In any case, systematic cross-linguistic investigations of feedback consistency involving both English and German are currently lacking. The onset entropy measures by Borgwaldt et al. (2004) seem to be the only objective measure that is currently available. It is noteworthy, though, that the literature seems to be in agreement that German shows an asymmetry in this regard with comparably high consistency in the spelling-to-sound, but low consistency in the sound-to-spelling direction (e.g., Görgen et al., 2021; Landerl et al., 2013; Moll et al., 2009). Therefore, differences between English and German should be more pronounced regarding feedforward consistency with English being more inconsistent than German, while both languages are described as inconsistent with regards to sound-to-spelling. Any empirical differences between the two languages in the investigations I describe in the second part of this thesis might therefore be better attributed to differences in feedforward consistency. It should be kept in mind, however, that a comparison between English and German feedback consistencies based on objective measures is based on a very slim data foundation and that the available data characterize German as more feedback consistent than English. Thus, it cannot be discarded that differences in feedback consistency might also contribute to any observed differences.

Because the term ‘orthographic depth’ is most commonly used to refer to feedforward consistency, I will continue to refer to English as a deep orthography and to German as a

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[3] Note that Landerl et al. (2013) use the term “orthographic complexity”, however, this is not equal to complexity as I have defined it. What they mean is what I refer to as “orthographic depth”, comprised of both complexity and consistency in the sense of Katz and Frost (1992).

shallow orthography based on the definitions in the previous section with German showing comparatively high (feedforward) consistency and medium complexity and English showing low (feedforward) consistency and high complexity. After having established a theoretical basis for orthographic depth and having described behavioral differences associated with this concept, in the next section, I will discuss cognitive and neurophysiological correlates of orthographic depth. Any behavior must have its roots in the brain, thereby behavioral differences might be related to differences in underlying cognitive and neuronal mechanisms. If orthographic depth shapes the way reading is acquired and how reading-related behaviors differ across languages including the processing of orthographic and phonological information, one major question is how this is related to underlying differences in the brain.

1.2.4 The neurobiology of orthographic depth

Both from an evolutionary and from a biographical perspective, written language is a comparatively recent development. The written language as a means of communication has only been established a couple of thousand years ago. In the scheme of the evolutionary history of mankind this is an extremely short period of time. Moreover, when we acquire the ability to read and write, our language system is usually very well established already. Children learn to read and write in school, usually around the age of six with slight differences across cultures and individuals. At this age, all other aspects of language have already been developed. This poses the question of how the human brain accommodates functions connected to written language. Because it is evolutionarily so recent, it is impossible that the brain has predestined areas for the representation of written language when we are born. Therefore, regions specialized to the processing of written word forms must be established through learning alone and must be reconciled with the existing language network in a way that allows for a dynamic interaction between phonological and orthographic information (Coltheart, 2014; Dehaene & Cohen, 2007). Because the neuronal specialization for the processing of written input purely relies on environmental exposure via education in a specific orthographic script, it is conceivable that the characteristics of the orthographic system influence the underlying brain mechanisms of orthographic processing and orthographic-phonological interaction. Thus, the functional organization of orthographic and phonological processing in the brain might look different for different orthographic depths.

Though the exact organization, interaction patterns and hemispheric lateralization patterns are being debated in the literature, the importance of the left superior temporal lobe for phonemic-phonological processing is undisputed (e.g., Friederici, 2011; Hickock, 2022;

Hickock & Poeppel, 2007, 2016; Liebenthal et al., 2013). The auditory signal is first processed for spectro-temporal characteristics in dorsal superior-temporal gyrus (STG) in the primary auditory cortex (Hickock, 2022; Hickock & Poeppel, 2007, 2016). Phonemic-phonological processing then engages posterior STG and inferior parietal cortex regions, but also extends to the superior temporal sulcus (STS) (Liebenthal et al., 2010; Hickock & Poeppel, 2007, 2016). Phonemic categorization processes have been found to be supported by middle and anterior STS. Liebenthal and colleagues (2005) presented familiar and unfamiliar consonant-vowel syllables in an auditory discrimination task. They found that the left middle and anterior STS responds more strongly to familiar syllables than to auditory signals of comparable complexity that could not be mapped onto phonemic categories. Contrarily, the dorsal STG was activated to the same extent by both types of stimuli, indicating that regions closer to the primary auditory cortex are less selective for phonemic-phonological processing and correspond to more general features of phoneme-like stimuli.

Training of unfamiliar non-phonemic auditory patterns increased both activation in left posterior STS and the P2 amplitude as measured by event-related potentials (ERPs) associated with left posterior STS as a generator. In comparison, long-term phonemic representations were associated with activation and P2 amplitude in middle and anterior STS (Liebenthal et al., 2010). Parieto-temporal regions including the supramarginal gyrus have also been found to be involved in phonemic-phonological processing and might code sensori-motoric information associated with phonemic-phonological processing (Dehaene-Lambertz et al., 2005; Hickock & Poeppel, 2007, 2016). Though the STG and STS have been proposed to be bilaterally involved in speech processing (Hickock, 2022; Hickock & Poeppel, 2007, 2016), functional differences have been found. The left auditory temporal lobe seems to be more sensitive to temporal changes while the right STS more strongly responds to spectral changes. Though both are relevant for phonemic-phonological processing, the left hemisphere might be more strongly involved when mapping sounds onto phoneme representations relies more on detecting fast acoustic changes (Dehaene-Lambertz et al., 2005; Liebenthal et al., 2013; Obleser et al., 2008; Zatorre et al., 2002).

Orthographic processing first involves detection of letter-specific visual characteristics associated with the ventral occipito-temporal lobe (vOT). The close proximity and organizational similarity to the ventral visual system involved in object recognition follows basic principles of how the brain is organized. Visual processing begins in the posterior occipital lobe in the primary visual cortex (V1) and is then processed along two visual streams. The dorsal visual stream follows the superior longitudinal fasciculus to posterior parietal areas and processes spatial relations among objects. The ventral visual stream runs from early visual cortices along the inferior longitudinal fasciculus to inferior temporal cortex and has been found to be involved in the identification of objects and their properties (Milner & Goodale, 2008; Ungerleider & Mishkin, 1982). The organization of the ventral visual stream follows a hierarchical order from lower-order visual features processed in more posterior visual cortices (V1 to V3) to higher order visual features being processed in more anterior parts of the ventral visual stream. In a similar fashion, it has been shown that the left vOT, specifically the fusiform gyrus, follows the same organizational pattern for the processing of written language. Vinckier et al. (2007) presented participants with false-font strings, strings of infrequent letters, strings of frequent letters but rare bigrams, strings with frequent bigrams but rare quadrigrams, strings with frequent quadrigrams and real words while measuring brain activity with functional magnetic resonance imaging (fMRI). They found a gradient of activation from posterior vOT to anterior vOT for lower level (fonts/letters) to higher level (quadrigrams/words) stimuli: The more word-like the stimulus was, the more anterior the activation in the left fusiform gyrus.

Thus, the anterior part of the vOT almost exclusively responds to abstract written word forms while being invariant for fonts, case and semantic categories and primarily responds to visible words, while activity to masked stimuli is usually reduced (Dehaene et al., 2001, 2002, 2004). This area has consequently been termed the Visual Word Form Area (VWFA) and can be seen as the neurobiological implementation of the (whole word) orthographic lexicon as proposed by psycholinguistic models of reading such as the DRC model. Fiebach et al. (2002) presented participants with highly frequent words, low frequent words and pseudowords in an fMRI study. They found higher activation in inferior occipital gyri and fusiform gyri bilaterally for high-frequency words compared to low-frequency words and pseudowords in agreement with the assumption of the VWFA as the whole word orthographic lexicon. Low-frequency words and pseudowords produced higher activation in left inferior frontal gyrus (IFG), specifically the pars opercularis, when compared to high-frequency words. The authors interpret the latter finding as reflecting grapheme-phoneme-conversion necessary to read pseudowords that do not have an abstract whole-word representation in the mental lexicon and, thus, will not activate the VWFA. They argue that these findings are in line with dual-route models of reading like the DRC model: The non-lexical route has its neurobiological implementation in the application of grapheme-phoneme rules represented in the left IFG, while the direct route involves abstract whole word forms of written words as associated with the left vOT.

Based on this neurobiological specification of the non-lexical and lexical route, reading in writing systems with different orthographic depths should involve these brain regions differently. Reverting back to the previous sections of this thesis, reading in shallow orthographies should rely more on sub-lexical information via grapheme-phoneme-correspondences of the non-lexical route, while reading in deep orthographies should more likely involve lexical strategies because grapheme-phoneme-correspondences are unreliable. Cherodath and Singh (2015) investigated 34 biliterate (Hindi – English) children in an fMRI study, with Hindi being defined as a shallow orthography and English as a deep orthography. Participants read words and non-words in both languages. While the authors found a qualitatively comparable reading network across both languages, differential activation in the pars opercularis of the left IFG was found for English non-words compared to English words but was much less pronounced for Hindi non-words compared to Hindi words. Processing of Hindi words and non-words involved the left IFG to almost the same degree but for English, high activation of the left IFG was only found for reading non-words. Word-reading in English involved the left IFG significantly less than non-word reading. This is in line with the assumption that word-reading in deep orthographies relies on a lexical route and does not involve grapheme-phoneme-conversion associated with the left IFG, while both word and non-word reading in shallow orthographies recruits brain regions associated with the non-lexical route.

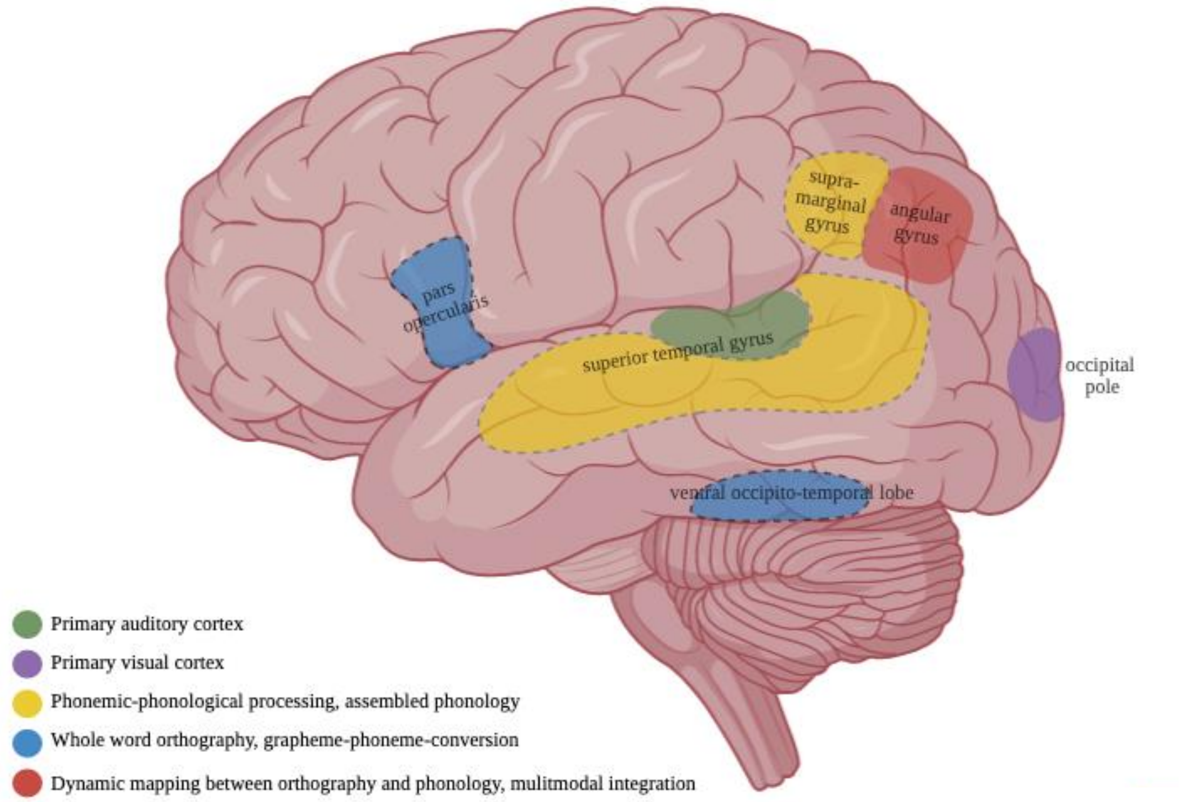
While the posterior part of the left IFG (i.e., pars opercularis) has been associated with phonological processing and grapheme-phoneme-conversion, it has been suggested that the anterior part (i.e., pars triangularis) might be associated with lexical-semantic processing and, thus, the left IFG might also correspond – at least in part – to the lexical route (e.g., Bookheimer, 2002; Hagoort, 2005; Heim et al., 2009). Moreover, other regions have been found to be associated with the non-lexical decoding of letter strings, namely the left inferior parietal lobe (IPL) as well as superior temporal regions. In a meta-analysis, Taylor et al. (2013) found evidence for activation in IPL for spelling-sound conversion across 36 neuroimaging studies. As described above, the IPL as well as superior temporal regions are involved in phonemic-phonological processing and might indicate involvement of assembled phonology in reading. As suggested by Katz and Frost (1992) in their Orthographic Depth Hypothesis (ODH), assembled phonology should play a more important role for shallow orthographies than for deep orthographies (see section 1.2.1 of this thesis). In agreement with this assumption, Paulesu et al. (2000) found stronger activation in right STG, specifically the planum temporale, for word and non-word reading in Italian, a shallow orthography, compared to reading words and non-words in English, a deep orthography, in a study with adults using positron emission tomography (PET). Moreover, they found stronger activation in the pars opercularis of the left IFG alongside the posterior inferior temporal lobe specifically for non-word reading in English in agreement with the findings of Cherodath and Singh (2015). Differences between the two orthographies were quantitative rather than qualitative in nature, indicating that reading across languages with different orthographic depths involves the same brain regions, but to a different extent.

These findings reveal a differential activation pattern in the reading network as a function of orthographic depth in agreement with the theoretical assumptions provided in previous sections. A stronger involvement of superior temporal regions in reading words and non-words in shallower orthographies indicates a reliance on assembled phonology in agreement with the ODH. Stronger involvement of VWFA in word and the left IFG in non-word reading in deeper orthographies indicates a strong distinction between a lexical and non-lexical route in agreement with the classic DRC model designed based on English. While word reading is based on the neurobiological implementation of a whole word orthographic lexicon in the vOT, termed the VWFA, non-word reading recruits brain regions associated with phonological processing and grapheme-phoneme-conversion located in the posterior part of the left IFG.

Notably, these findings have been replicated in bilingual adults in a variety of different studies (e.g., Buetler et al., 2014; Das et al., 2011; Jamal et al., 2012; Kumar, 2014; Nelson et al., 2009). For example, Jamal et al. (2012) investigated single-word reading in Spanish-English bilinguals, with Spanish being considered shallow and English being considered deep. They found a stronger involvement of left middle temporal gyrus and STS associated with phonemic-phonological processes and assembled phonology in Spanish compared to English. However, when the same subjects read English words, stronger activation in the left middle and superior frontal gyrus was found. Strikingly, Buetler et al. (2014) using EEG showed that the differential recruitment of brain regions in bilinguals is not dependent upon the stimuli but solely on the linguistic context. They presented French-German bilinguals with the same pseudowords embedded in a German context or a French context. Note that German and French differ specifically with regards to complexity with French being highly complex and German being comparably simple, while both can be considered as consistent orthographies. The authors found different topographical distributions of a component arising 300 to 360 ms after stimulus onset for the two contexts indicating involvement of different neuronal generators in reading in the two orthographies. This indicates a flexible recruitment of different brain regions in adult bilingual reading as a function of the orthographic depth of the target language. However, these studies were conducted with early/simultaneous bilinguals, thus, findings for late bilinguals are currently lacking.

Figure 4

Brain network for the processing of orthographic and phonological information as a function of orthographic depth



Note. Created in biorender.com.

Dashed outlines indicate differential involvement in orthographic processing as a function of orthographic depth. Indicated in green is the primary auditory cortex in the dorsal superior temporal gyrus (STG) involved in the spectro-temporal analysis of the speech signal. Yellow areas indicate phonemic-phonological processing in the STG, the superior temporal sulcus (STS) and the inferior parietal lobe (IPL) including the supramarginal gyrus. These areas are also involved in reading in shallow orthographies via assembled phonology. Marked in purple is the primary visual cortex associated with the analysis of visual information. Blue colored areas reflect word and non-word reading in deep orthographies. The Visual Word Form Area (VWFA) in the ventral occipito-temporal cortex corresponds to the orthographic lexicon and is associated with reading of whole word forms, while the pars opercularis in the left inferior frontal gyrus (IFG) is connected to grapheme-phoneme-conversion. Indicated in red is the angular gyrus associated with the dynamic mapping between orthography and phonology with a special involvement in cross-modal tasks. The figure only depicts the left hemisphere.

Please note that primary auditory and visual processing as well as phonemic-phonological processing are assumed to take place bilaterally.

Booth et al. (2004) tested 9- to 12-year-old children and adults with rhyming and spelling judgments in English in the visual and auditory modality using fMRI. They found greater activation in left fusiform gyrus for visual tasks consistent with greater activation in the VWFA for processing of visual whole words. Greater activation for tasks in the auditory modality was reported in the left STG consistent with phonemic-phonological processing. Strikingly, in the auditory spelling task, which involves access to orthographic information, both children and adults showed activity in the VWFA, while in the visual rhyming task, which necessitates access to phonological representations, activation in the left STG was found. This indicates that even in the absence of a visual stimulus, access to orthographic information in auditory processing activates brain regions associated with reading and in a similar manner access to phonological information during visual processing activates brain regions associated with phonological processing. This is in line with a bimodal processing account of orthography and phonology as implemented in the BIAM and as shown in the previous sections of this thesis. Moreover, the angular gyrus in the IPL showed enhanced activation in all cross-modal tasks that involve a dynamic mapping between orthographic and phonological representations. Thus, it might play an important role in the dynamic interaction between orthography and phonology. This is in line with the general description of the angular gyrus as a hub for the integration of information from multiple modalities across different cognitive functions (e.g., language, memory, attention) (Bonnici et al., 2016; Niu & Palomero-Gallagher, 2023). This region showed developmental differences and was more strongly activated in adults indicating that efficiency in the mapping from phonology to orthography and vice versa increases across development.

From these findings, I derived a brain network of bimodal orthographic and phonological processing in languages with different orthographic depths. The relevant brain areas and their assumed functions as identified in this section are visualized in Figure 4.

Throughout this section, I have shown that orthographic depth, i.e., the complexity and consistency of grapheme-phoneme-correspondences, is not a purely descriptive construct but is widely recognized as the most important feature of an orthographic system to explain all reading-related behaviors in beginning and skilled readers. These behaviors have their roots in the underlying mechanisms of the brain that are modulated by the orthographic depth of the target language. While the reading network has been found to involve the same brain regions across different languages, the activation patterns across this reading network differ as a function of orthographic depth. Brain regions associated with assembled phonology, specifically the left STG and IPL, have been found to be more involved in reading in shallow orthographies, while regions associated with non-lexical decoding and lexical whole word processing such as the left IFG and left vOT, respectively, have been found to be more involved in reading in deeper orthographies. Lastly, the same brain regions have also been found to be involved in bimodal language processing, i.e., when phonological and orthographic information is accessed even in the absence of auditory/visual stimuli.

The neurobiological differences in orthographic processing across languages make it important to consider neuroscientific methods in its investigation. Though in this section, brain imaging methods such as fMRI or PET have received a specific focus due to their importance in specifying the localization of cognitive mechanisms, the neurobiological differences underlying the bimodal processing of orthography and phonology can also be captured with neurophysiological methods because the differential involvement of different neuronal generators causes differences in topographical distributions and neurophysiological components. These components will be described in the following section with a focus on event-related potentials (ERPs) and time-frequency (TF) measures that were used in the studies described in the second part of this thesis.

1.3 Neurophysiological correlates of orthographic and phonological processing

> Cognitive electrophysiology is the study of how cognitive functions (including perception, memory, language, emotions, behavior monitoring/control, and social cognition) are supported or implemented by the electrical activity produced by populations of neurons. Cognitive electrophysiology […] is useful because it is more sensitive than behavioral measures such as reaction time or introspective self-report and therefore is better able to dissociate cognitive processes and their subcomponents. (Cohen, 2014, p. 3)

The previous section on the neurobiology of orthographic depth has shown that cognitive abilities such as reading as well as their behavioral correlates reflected in reading-related measures such as reading speed and accuracies across different tasks have their roots in the neurobiological mechanisms of the brain. Orthographic depth has been shown to influence brain activity in the regions involved in these cognitive processes, which in turn will influence neurophysiological mechanisms underlying the processing of orthography and phonology. While behavioral measures have been used for a long time as a means to gather information about how cognitive abilities develop and function in different populations, the behavioral output can only be an indirect approximation of the cognitive processes. The behavioral output that is measured is affected by a variety of factors that do not correspond to the cognitive process of interest such as attention, executive control, or motor functions. If we want to learn more about differences in the cognitive mechanisms underlying the processing of orthography and phonology in different orthographic systems, we need to consider more direct methods that are suitable to investigate the cognitive process as it unfolds. Electroencephalography (EEG) allows to measure brain responses to linguistic stimuli in a millisecond range and is therefore particularly suitable to investigate orthographic and phonological influences on word processing because these occur early in processing at a sub-lexical level. Thus, EEG makes it possible to track the different cognitive subprocesses with high temporal resolution (Luck, 2014; Rommers & Federmeier, 2017).

The EEG records post-synaptic potentials of many thousands of pyramidal cells oriented perpendicular to the surface of the cortex. The electrical activity at the post-synaptic membrane created by neurotransmitters binding to receptors and the corresponding flow of ions across the cell membrane creates an electrical dipole that can be measured on the scalp if the dipoles of a large number of neurons add together. This is only possible if the neurons are oriented in a similar direction, otherwise the dipoles will cancel each other out. This characteristic is mostly found for pyramidal cells, consequently, the scalp-recorded EEG almost selectively measures electric activity from pyramidal neurons in the cortex, which is only a fraction of the brain activity that takes place at any given moment. However, this makes the EEG signal an instantaneous, direct, and continuous measure of neurotransmission-mediated neural activity and sets it apart from secondary measures of neural activity such as BOLD (blood oxygenation level dependent)-related methods like fMRI (Luck, 2014; Rommers & Federmeier, 2017).

A prominent disadvantage of EEG compared to the latter methods is the poor spatial resolution. Because the electrical activity is dispersed through the scalp, measuring a certain response at a specific electrode does not reveal where the signal originated from. Thus, the topographical localization of an effect at the scalp is not equal to the location of the source of the signal. More severe than the dispersion through the scalp, however, is the fact that multiple sets of dipoles can create the exact same voltage distribution at the scalp, and it is impossible to know which localization and orientation of the dipoles is the correct one (so-called "inverse problem"). Even though methods have been developed to approximate a solution to this problem, research questions connected to the localization of a specific cognitive process in the brain rather than its temporal characteristics are better investigated with other methods. Nonetheless, the topographical localization of an effect can provide important information about the underlying neuronal generators, especially with regards to the differentiation of two effects (Buetler et al., 2014; Luck, 2014; Perre et al, 2009).

The EEG continuously measures all ongoing brain activity irrespective of the underlying functional mechanism. Neurophysiological correlates of orthographic and phonological processing can be derived from the EEG signal via specific signal processing techniques. Most neurophysiological language studies rely on event-related potentials (ERPs), though in the last decades, time-frequency (TF) measures have been established as another means to gain information about cognitive processes contained in the EEG signal. I used both methods in my studies to investigate the bimodal processing of spoken words, thus, they will be briefly discussed in the following.

1.3.1 Event-related potentials (ERPs)

ERPs contain the brain response to a specific stimulus (or "event") extracted from the continuous EEG signal. Because the ongoing brain activity that is unrelated to the processing of a linguistic stimulus is spontaneous and fluctuates randomly, it is possible to extract the stimulus-related activity through simple averaging of the voltage at each time-point. The unrelated activity (called "noise") is cancelled out and the stimulus-related activity (the "signal") remains if enough data is available. Therefore, EEG experiments often consist of many stimuli pertaining to the same experimental condition, so that responses to the same type of stimulus can be averaged together to cancel out as much of the noise as possible. The more data can be averaged, the better the signal-to-noise ratio. The remaining ERP is plotted as voltage fluctuations over time. The voltage deflections can be either negative or positive and are connected to specific functional processes. These so-called "ERP components" are usually named by their polarity (P for positive deflection, N for negative deflection) and their peak latency. Because ERPs have an extremely high temporal resolution, the deflections portray the time-course of language processing with a very high precision and have been used to gather information about the exact pattern of activation of linguistic information as it unfolds over time (Friederici, 2011; Luck, 2014; Rommers & Federmeier, 2017).

Two ERP components that are relevant for the empirical studies in the second part of this thesis are worth mentioning here: The N400 and the N250 components. Occurring between 300 and 500 ms with a peak at 400 ms after stimulus onset at centro-parietal electrode sites, the N400 was originally measured in relation to semantic anomalies and violations. It has, however, been found that this component also appears in relation to non-linguistic stimuli and can frequently be observed in context and expectation violations including priming studies (Kutas, 2011; Rommers & Federmeier, 2017). It is often reported in phonological and orthographic priming both in visual and spoken word recognition with a reduced amplitude for primed conditions relative to an unprimed control condition (e.g., Grainger et al., 2006; Holcomb & Grainger, 2006; Perre et al., 2009). The N250 component has been observed in studies using pseudohomophone and transposed letter (TL) priming in visual word recognition. The former is associated with phonological processes, while the latter is associated with orthographic processes. Similar to the N400 component, lower amplitudes reflect priming compared to unprimed conditions. The topographical distribution of the N250 varies across studies and has been reported at both anterior and posterior electrode sites (e.g., Eddy et al., 2016; Grainger et al., 2006; Mead et al., 2022). The N250 component has been associated with pre-lexical access while the N400 is usually connected to lexical processing (Grainger et al., 2006).

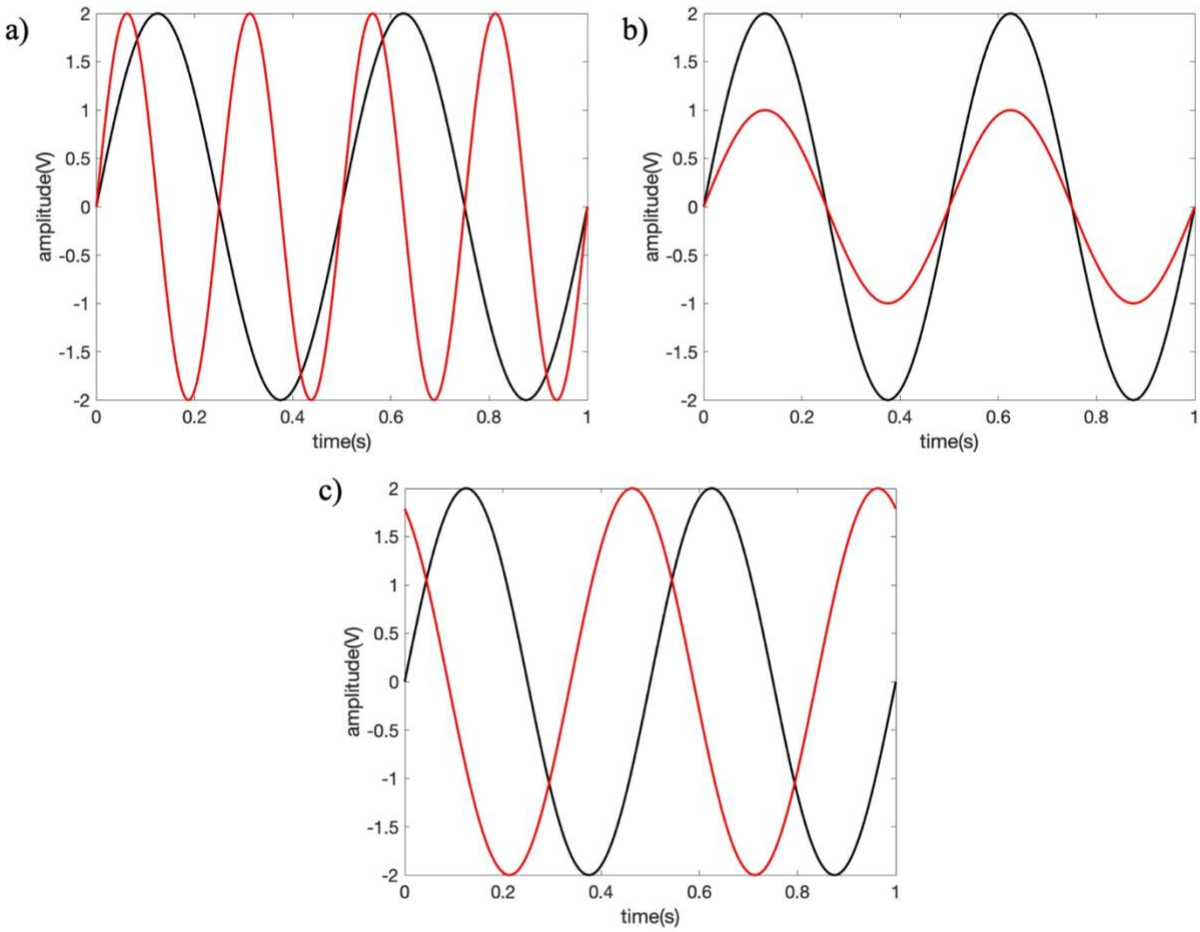
Due to their high temporal resolution, ERPs have revealed important information about the bimodal processing of spoken words, such as the simultaneous, bottom-up activation of phonological and orthographic information during word processing rather than a late, top-down modulated involvement of orthography. However, ERPs are limited in their interpretational value for the investigation of the underlying cognitive processes because they reflect relatively little information contained in the EEG signal. Specifically, time-locked, but non-phase-locked dynamics are lost in the averaging process of the ERP, but are recoverable using other methods, such as time-frequency measures (Cohen, 2014; Morales & Bowers, 2022).

1.3.2 Time-frequency (TF) measures

The electrophysiological signal measured via EEG contains more information than ERPs can reveal. Particularly relevant is that neurophysiological activity is oscillatory in nature, which means that the signal is not only comprised of a particular voltage amplitude at a given time point, but also of characteristics related to the oscillations, namely frequency, power, and phase. Neural oscillations are rhythmic activity that reflects the excitability of neuronal populations. While ERPs only reflect voltage changes over time, thus ignoring the frequency domain, time-frequency (TF) analyses look at both domains simultaneously thereby revealing more information about cognitive mechanisms underlying specific processes. Consequently, they can be a useful addition to ERP analysis to find out more about the cognitive processes under investigation as measured by EEG (Cohen, 2014; Morales & Bowers, 2022). Frequency can be defined as the speed of the oscillation, i.e., the higher the frequency, the more oscillations can take place in a given unit of time. Consequently, frequency is usually measured as the number of cycles per second and given in hertz (Hz), where 1 Hz means one cycle per second. Power is the amount of energy in a specific frequency band. Power is equal to the squared amplitude of the oscillation. Phase is the position along the wave at a given time point and is measured in degrees or radians (Cohen, 2014). Figure 5 illustrates these concepts.

Figure 5

Illustration of the time-frequency related concepts of frequency, power, and phase



Note. Subplot a) illustrates the concept of frequency. The black curve shows a sine wave at a frequency of 2 Hz, while the red curve shows a sine wave at 4 Hz. In a time period of 1 second, the black sine wave completes two full cycles, while the red curve completes four. Subplot b) illustrates the concept of power. The black curve shows a peak amplitude of 2 volts while the red curve only has a peak amplitude of 1 volt. Power is amplitude squared, thus the higher the amplitude, the higher the power. Subplot c) illustrates the concept of phase. The black curve has a phase value of 0 degrees, while the red curve shows a phase value of 90 degrees. Thus, the red curve is shifted relative to the black curve and the oscillations are not aligned.

TF measures are extracted from the continuous or event-related EEG recording via convolution. Convolution is the extraction of commonalities between two signals by applying the dot product at each element repeatedly over time. The convolution theorem states that the Fourier transform of the convolution of two signals in the time domain equals the product of the two signals in the frequency domain. Thus, convolution can be performed either in the time or in the frequency domain. Via Fourier transformation, the voltage changes over time can be transformed without loss of information into the frequency domain. Likewise, information from the frequency domain can be transformed back into the time domain using the inverse Fourier transform. Hence, the Fourier transform is a perfect frequency-domain representation of a time-domain signal. However, the Fourier transform captures global frequency information that persists over an entire signal. This is often not adequate for electrophysiological data, because they contain multiple short periods of characteristic oscillations. Therefore, TF analysis mostly uses wavelet transformation to get from the time to the frequency domain and vice versa. Wavelets are short wave-like signals that are localized in time and can have a variety of different forms and parameters. Sliding a wavelet over the time-series signal and multiplying wavelet and signal at each point in time reveals when and to what extent the signal contains features that look like the wavelet. Using multiple wavelets with different frequencies, thus, allows to extract information about whether and when these frequencies are present in the EEG signal. Because the wavelet is localized in time and contains a specific frequency, it can extract both local spectra and temporal information simultaneously. However, there is a time-frequency tradeoff: High resolution in one domain comes with low resolution in the other and vice versa. Usually, it is of interest to have higher frequency resolution at lower frequencies, because small changes in frequency at the lower spectrum make a greater difference than changes at the upper frequency spectrum. At higher frequencies, time resolution is more important, because a full cycle of a high frequency oscillation takes less time and local frequencies can change faster (Cohen, 2014; Morales & Bowers, 2022).

Brain oscillations contain multiple frequencies at once that can be disentangled using wavelet convolution. These so-called frequency bands are linked to different cognitive processes that take place simultaneously while each cognitive process utilizes different frequency ranges. The most relevant frequency bands for cognitive science are delta (2-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (15-30 Hz), lower gamma (30-80 Hz) and upper gamma (80-150 Hz). It should be noted, though, that the boundaries between the frequency bands are not fixed and reported differently in the literature (Cohen, 2014). An important brain mechanism associated with oscillatory activity is the synchronization and desynchronization of neuronal groups in different cortical regions or across different trials. The temporary link established between synchronized neuronal populations allows for efficient communication between them, thus establishing a dynamic, functionally specified network that enables the integration of information in order to make sense of the linguistic input (Bastiaansen et al., 2005; Weiss & Mueller, 2012). Synchronization between neuronal populations is established by equal firing rates. This leads to aligned phases which will also increase power in a specific frequency band. Phase alignment is typically termed “phase synchrony” or “phase coherence”.

This is reflected in measures such as inter-trial phase coherence (ITPC) or inter-channel phase coherence (ICPC) (Cohen, 2014; Morales & Bowers, 2022). It is important to note that some frequency bands function via inhibition while others rely on excitatory processes. For example, increases in power and ITPC in the alpha band are observed when participants are less engaged in task demands and when their eyes are closed, because the processing of stimuli is inhibited in these states. Thus, reduced alpha band activity, i.e., alpha band desynchronization, is connected to attention towards stimuli (Foxe & Snyder, 2011; Klimesch, 2012). Contrarily, the gamma band is connected to excitation. As such, higher power and ITPC in the gamma band are observed for conceptual integration of coherent sentences as opposed to incoherent sentences (Bastiaansen & Hagoort, 2015).

Compared to the technique of ERPs, TF measures in cognitive-linguistic research are comparably young, consequently, much less is known about how TF measures relate to cognitive-linguistic processes which can make their interpretation difficult. However, the awareness of the importance of brain oscillations for the investigation of language processing has increased over the last two decades. As a consequence, specific linguistic functions have been observed in certain frequency bands. For example, decreases in alpha and beta activity have been associated with sensory and sensory-motoric processing of linguistic input, respectively, and are involved in the processing of properties of the word forms, action semantics or word generation tasks (e.g., Bastiaansen et al., 2005, 2008; Weiss & Mueller, 2012). Bishop et al. (2011) found that auditory discrimination of tones and syllables as measured by the mismatch negativity (MMN) ERP component relies on phase synchronization in the theta range. Both MMN amplitude and phase synchrony as measured by ITPC in the theta band increase with age throughout development from childhood into adulthood, revealing that the sensitivity to auditory stimuli still increases after childhood. Increases in theta power have also been observed for lexical-semantic retrieval during sentence processing and visual lexical decision (Bastiaansen et al., 2005, 2008). However, semantic processing has also been associated with the gamma frequency band. Hagoort and colleagues (2004) investigated word meaning and world knowledge violations and found qualitatively and quantitatively similar N400 components for both. However, the two types of violations showed specific patterns of TF activity: Power increases in the gamma frequency range were selectively associated with the violation of world knowledge, while increases in the theta band were associated with word semantic violations indicating that the different types of information processing rely on different neuronal networks.

The gamma band has also been found to be relevant for phonological processing. Wheat and colleagues (2010) investigated the involvement of phonology in visual word recognition and found increased TF power in the gamma band (30-40 Hz) for pseudohomophones (e.g., *brein–BRAIN*) compared to orthographic controls (e.g., *broin–BRAIN*) within the first 100 ms of target word onset. This early effect of phonological involvement was limited to induced power, which is not captured by ERP components and can only be revealed by TF measures. Matsumoto and Iidaka (2008) presented participants with repeated words (e.g., *lemon–lemon*), homophone pairs (e.g., *pair – pear*) and an unrelated control condition (e.g., *leaf – car*) in Japanese Kanji script. They found that both repetition and homophone priming led to decreases in power and ICPC in the gamma frequency range. The authors interpret these findings to reflect a repetition suppression effect connected to more effortless processing of a target following a related prime word compared to an unrelated word (Nordt et al., 2016). The gamma range is associated with the formation of higher order cognitive representations and might be important for priming studies in general. However, gamma band synchronization has also been found to be involved in phonemic-phonological processing of native and non-native speech sounds (e.g., Lehongre et al., 2013; Ortiz-Mantilla et al., 2013; Wagner et al., 2022). Bizas et al. (1999) found higher delta power for orthographic compared to visuospatial tasks and related this power increase to higher orthographic processing demands. However, they also found increased delta power for a semantic versus an orthographic task. Thus, increases in delta power might be connected to task complexity rather than reading-related behavior.

These examples reveal the importance for TF measures in the investigation of language-related processes as they can reveal more information about the underlying cognitive mechanisms. It also becomes clear, that TF measures can reveal processing differences and effects that are not captured by ERPs. However, due to the comparably recent establishment of TF methods, much is still unknown about how they relate to specific cognitive-linguistic processes. TF-related activity in the same frequency band can be related to different functions while the same function is associated with more than one frequency band. Moreover, studies investigating the processing of orthographic information including orthographic priming using TF measures are currently lacking. In fact, I could not find a single study reporting TF measures for orthographic processing. Hence, it will be difficult to establish *a priori* assumptions for expected effects in the empirical studies in the second part of this thesis. Nonetheless, I deem it important to include TF measures in my analyses to get more information about the mechanisms underlying the bimodal processing of spoken words.

1.4 The current studies

The acquisition of the written modality of language changes the way in which the language processing system is organized. The written form of the word needs to be accommodated into the existing phonological-semantic structure and linked to the corresponding phonological and semantic representations. This leads to a dynamically interacting system that engages both phonological and orthographic information during word processing in either modality. Via the co-activation of both types of representations, word processing becomes bimodal in nature both at a pre-lexical and lexical level. This is revealed in the fast and automatic activation of phonological information during visual word processing and of orthographic information in spoken word processing at latencies way before the lexical access. While the involvement of phonology in reading is undisputed in the literature and has been accepted for quite some time, the automatic influence of orthography in spoken word recognition is a more recent finding. Nonetheless, extensive evidence suggests that orthography is as important for the processing of spoken words as phonology is for reading.

However, this extensive evidence is limited to English and French, two languages with particular characteristics regarding their orthographic systems. The English orthography is exceptionally complex and inconsistent, meaning that many complex rules are required to comprehensively map graphemes onto phonemes and a lot of irregular words remain that cannot be read based on grapheme-phoneme-rules. This makes English an orthographically deep language with regards to both components. The French orthography is even more complex than the English one but shows a high degree of consistency. Thus, French is of high orthographic depth with regards to the complexity component, but very shallow with regards to the consistency component. The little available evidence on the bimodal processing of orthography and phonology in other languages such as Serbo-Croatian (Frost & Katz, 1989) and Portuguese (Ventura et al., 2004) suggests that bimodal processing is influenced by the orthographic depth of the language and is diminished in shallow orthographies. However, these studies only rely on behavioral measures and to date no neurophysiological data is available that investigates the effect of orthographic depth on the bimodal processing of spoken words.

Based on these behavioral studies and the high importance of the orthographic depth for all reading-related processing as well as for the representation of orthography and phonology and their neurobiological substrates, it must be assumed that orthographic depth also modulates bimodal word processing. In the same way as reading development, skilled word reading and reading-related behaviors vary substantially across languages, I suggest that the bimodal processing of spoken words is not generalizable to languages with different orthographic depths but is modulated by the language-specific characteristics of the orthographic system. However, no studies yet exist that systematically investigate the effect of orthographic depth on the bimodal processing of spoken words in the same population. Moreover, if orthographic depth modulates bimodal word processing, the question arises, how individuals with orthographic representations of two languages with different orthographic depths process spoken input in their L1 and L2.

Consequently, the aims of this thesis are twofold: First, I want to investigate whether the bimodal processing of spoken words that has reliably been found for deep orthographies such as English and French can also be found in a shallow orthography. Second, if orthographic depth influences bimodal spoken word processing, I want to investigate how bilingual individuals with linguistic representations of languages with different orthographic depths process their L1 and their L2. Of specific interest is here, whether bilinguals can flexibly adapt processing mechanisms to the target language or whether they transfer their native processing to the L2. The studies presented hereafter aim to answer these research questions by investigating orthographic influences on spoken word recognition in late German-English bilinguals in their native and second language. As has been established previously, German can be considered a shallow orthography compared to English, with a comparatively simple and consistent system, while English is exceptionally complex and inconsistent and often considered the deepest orthographic system among the European languages. Thus, German and English differ in orthographic depth with respect to both of its components. Thereby, the studies enable the systematic comparison of two Germanic languages with comparable syllabic complexity, but different orthographic depths, while controlling for cultural influences such as the educational and language background of the participants by testing the same population in both languages.

Two series of experiments were conducted. In the first study, I used an established paradigm to investigate bimodal spoken word processing and replicated the experiment by Perre and colleagues (2009) introduced in previous sections that used an auditory priming paradigm to investigate effects of orthographic and phonological overlap on spoken word processing. The original study was conducted in English with English native speakers and used behavioral as well as EEG measures. To answer the first research question, I constructed a comparable stimulus set in German and tested German native speakers with the same paradigm as Perre et al. (2009) using the same methods. If orthographic depth modulates the bimodal processing of spoken words, the results of the experiment in German should differ from the results found by Perre and colleagues (2009) in English. ERPs and TF measures are used to provide information about the nature of these assumed differences. To address the second research question, I tested German native speakers in their second language English using the English stimuli provided by Perre et al. (2009). If bilinguals flexibly adapt processing to the target language, the results should be similar to those of the native speakers tested by Perre et al. (2009). However, if bilinguals transfer processing mechanisms from their L1 to their L2, results should be comparable to the German experiment.

A second series of experiments was conducted to address methodological issues of the auditory priming paradigm used in the first study and to replicate the results. Here, I used a transposed letter (TL) priming paradigm, a research design that is well established in the investigation of orthographic priming in visual word recognition. In a first experiment, I used a unimodal (visual prime – visual target) design with TL and repetition primes compared to a control condition to replicate previously found TL effects in late German-English bilinguals in both of their languages with behavioral measures. This was important to ensure that the stimulus material and the experimental design were suitable to evoke the desired effects because in the second and third experiments I used a cross-modal (visual prime – auditory target) design which had never been attempted before. The cross-modal paradigm was used to prompt bimodal processing in accordance with assumptions of the BIAM. In Experiment 2, I used the same stimuli as in Experiment 1 in a cross-modal design and tested late German-English bilinguals in their L1 German and their L2 English using behavioral and neurophysiological measures. The prime duration was manipulated to test effects of prime visibility on processing performance. In Experiment 3, a similar group of participants was tested with the same methods, but pseudohomophone primes were used instead of repetition primes to disentangle orthographic and phonological effects on spoken word processing. If orthographic information is involved in spoken word processing irrespective of the orthographic depth, the results should not differ between the German and English experiments. However, if orthographic depth affects bimodal word processing, processing differences should be observed.

2. The role of orthography in auditory priming

2.1 Introduction

It has been established in previous sections of this thesis that spoken word processing is bimodal in nature involving phonological and orthographic representations via co-activation in the mental lexicon as implemented in the BIAM. Extensive empirical evidence collected in English and French native speakers support these assumptions. Perre and colleagues (2009) used an auditory priming paradigm and presented English native speakers with English word pairs that overlapped orthographically and phonologically (O+P+; e.g., *beef – reef*), phonologically but not orthographically (O-P+; e.g., *leaf – reef*) or not at all (O-P-; e.g., *sick – reef*). They recorded behavioral and EEG measures and found lower reaction times, higher accuracies and lower N400 amplitudes for the O+P+ condition compared to the O-P+ condition. This was taken as evidence that orthographic overlap in addition to phonological overlap facilitates processing of the target word even when the word pairs are only presented auditorily. Both conditions with phonological overlap showed reduced reaction times, higher accuracies and lower N400 amplitudes compared to the unprimed control condition. The effect of orthographic overlap (O+P+ compared to O-P+ and O-P-) produced an N400 effect at central electrode sites starting at 400 ms post target onset. The effect of phonological overlap (O+P+ and O-P+ compared to O-P-) showed a different topographical distribution and was localized at parietal electrode sites with the same latency. This indicates that orthography influences spoken word processing in an on-line manner and can be differentiated from phonological contributions via topographical differences in the effects. Because the same target word is compared across conditions and the phonological overlap is controlled, the processing differences between the O+P+ and the O-P+ condition must be attributed to the orthographic manipulation[4].

However, it has long been known from reading research that the processing of orthographic input differs substantially across languages as a function of the orthographic depth of the specific script. The orthographic depth not only has implications for reading acquisition and performance, but also for the representation of orthography and phonology in the brain as well as the underlying brain mechanisms. Differences in reading performance have been attributed to 'psycholinguistic grain sizes' that vary as a function of orthographic depth (Goswami, 2010; Ziegler & Goswami, 2005). For English, grapheme-to-phoneme-correspondences are highly irregular, therefore, relying on small orthographic units is not feasible. Instead, orthographic chunks of larger grain sizes like rimes and whole-words exhibit more reliable spelling-to-sound consistencies in deep orthographies. Indeed, a strong role of rime effects in reading has been reported for English children, whereas German children rely more strongly on small orthographic units at the level of phonemes. These findings suggest that orthographic depth strongly affects the level of orthographic units represented in phonology and vice versa (Goswami et al., 1997, 1998; Goswami et al., 2005; Ziegler & Goswami, 2005). Consequently, different patterns of activation of orthography during spoken word recognition

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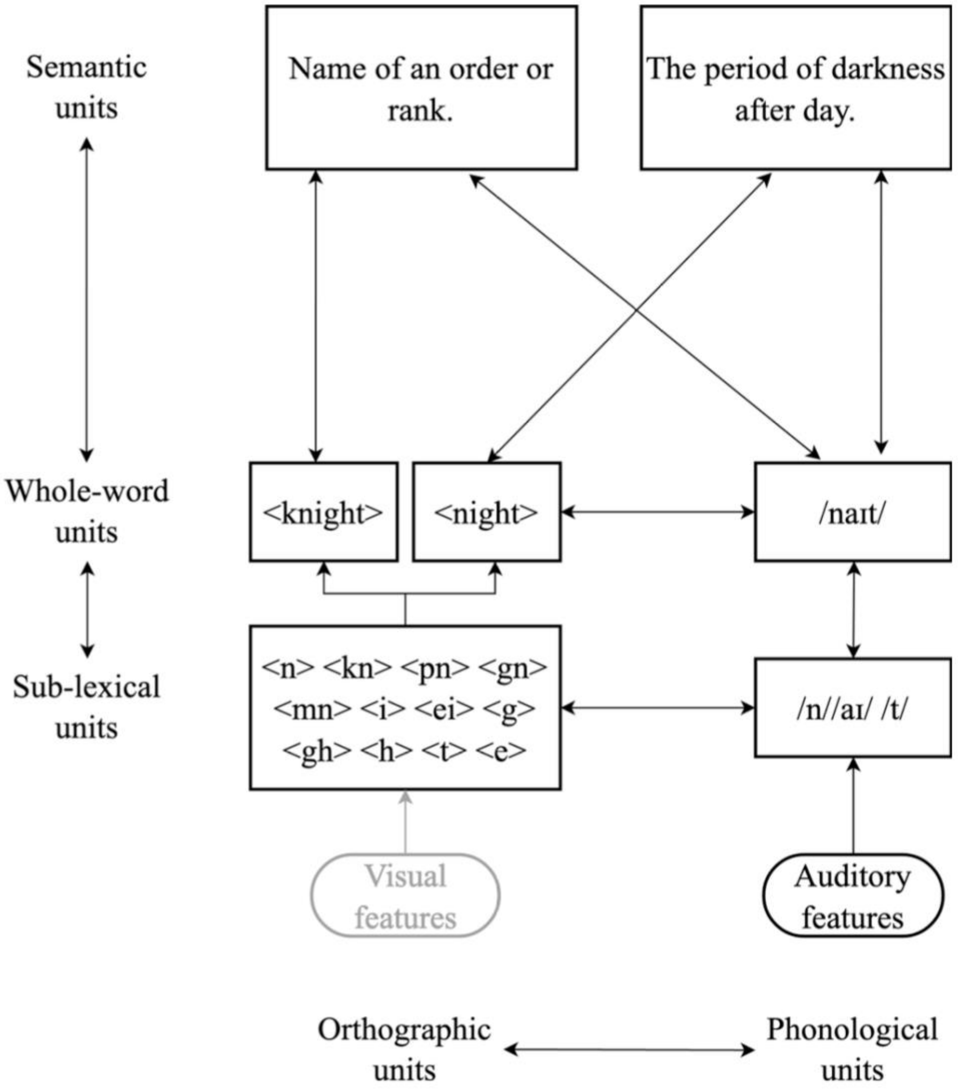
[4] Please note that the following information was in part published previously and parts of the following chapter were taken from Türk and Domahs (2022) and adapted for this thesis.

are conceivable depending on the orthographic depth of the language. The simultaneous activation of orthography and phonology at the level of rimes and whole words might be efficient in English, while for German, the effect of orthography on phonology might be restricted to smaller sub-lexical units.

Figure 6

Activation of phonological word /naɪt/ within the framework of the BIAM



Note. From “Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language”, by S. Türk and U. Domahs, 2022, *Brain and Language*, *235*, 105186, p. 3 (https://doi.org/10.1016/j.bandl.2022.105186). Copyright 2022 by Elsevier.

Moreover, deep orthographies contain a higher number of homophonic heterographs (e.g., night – knight, sight – site – cite, life – live) than shallow orthographies. A bimodal processing of phonology and orthography in spoken word recognition might therefore be advantageous in accessing the semantic meaning of a word in the mental lexicon. If, for example, the phonological word /naɪt/ is presented without context, the BIAM suggests that the articulatory features will activate the sub-lexical phonological units /n/, /aɪ/, /t/ that trigger the corresponding sub-lexical orthographic units < n>, <kn>, <pn,>, <gn>, <mn>, <i>, <ei>, <g>, <h>, <t>, <e >. The sub-lexical units will activate the phonological whole-word unit /naɪt/ and the orthographic whole-word units <night> and <knight>. This is illustrated in Figure 6. While the phonological word is equally compatible with two meanings, the orthographic word forms are connected to only one of two distinct semantic units. The additional information provided by the orthographic representations such as the frequency of the orthographic word forms and the orthographic neighborhood sizes help to select one of the two semantic units. The semantic unit connected to the orthographic word form with the highest frequency and the highest neighborhood size will be selected preferentially as it is the most likely candidate. Thus, bimodal processing by activating phonology and orthography simultaneously helps to map the spoken input onto the most adequate semantic unit.

This does not hold for languages with a shallow orthography. In shallow orthographies, the mapping between phonemes and graphemes is highly consistent, hence, the number of homophonic heterographs is much smaller. If most homophones are homographs, bimodal processing will not be helpful and might even lead to higher processing costs, because it would lead to activation of representational units that do not add any information in addition to the phonological units already activated by the articulatory features. Indeed, there is empirical evidence that bimodal processing is influenced by orthographic depth: In a bimodal research paradigm, Frost and Katz (1989) simultaneously presented spoken and written words in a same/different task. Word pairs were presented in three different conditions: clear print and clear speech, clear print and degraded speech and clear speech and degraded print. Participants had to decide whether the word pairs were identical or different while reaction times and accuracies were recorded. The authors found that degradation of either speech or print led to poorer performance for English compared to Serbo-Croatian participants. The authors conclude that the detrimental effect of degradation in English can be attributed to differences in the writing systems with English having the deeper orthography. They argue that the relations between orthography and phonology are structurally different in the two writing systems shaped by the orthographic depth. Deep writing systems have complex grapheme-phoneme-correspondences, therefore, connections between the orthographic and phonological networks on a sub-lexical level are less straightforward than for shallow writing systems, because a higher number of connections is necessary to account for all grapheme-phoneme-correspondences. Due to the high complexity of these connections, compensatory activation is less effective in English than in Serbo-Croatian. In shallow orthographies, compensation for degradation in one modality is easier as connections beneath the whole word level are more straightforward.

In relation to the orthographic consistency effect, two studies comparing Portuguese and French in a lexical decision task found a diminished effect in Portuguese that was attributed to the orthographic depth. In both studies, participants were auditorily presented with words whose phonological rime could only be spelled in one way (consistent condition) and words whose phonological rime can be spelled in multiple ways (inconsistent condition). For both experiments, reaction times were lower in the consistent compared to the inconsistent condition, however, differences were more pronounced for French than for Portuguese. Pattamadilok, Morais et al. (2007) computed consistency ratios for French and Portuguese and found a higher overall consistency for the Portuguese language. When comparing the effect sizes of the consistency effects in Pattamadilok, Morais et al.'s study in French and Ventura et al.'s (2004) study in Portuguese, the authors reported a stronger consistency effect in French. The authors conclude that the Portuguese listeners were less sensitive to orthographic inconsistencies than the French listeners, who are confronted with frequent inconsistencies due their relatively deep writing system (Pattamadilok, Morais et al., 2007).

One methodological issue with these studies is that different populations of participants are compared leading to influencing factors that lie in the participants such as the educational and language background. Thus, differences in orthographic processing can not only be attributed to the orthographic depth of the native language, but also potentially to differences in the way reading is taught in different countries (see also Ziegler & Goswami, 2005). Moreover, both studies relied on behavioral measures only and to date no neurophysiological evidence is yet available that investigated the influence of orthography on the processing of spoken words in a language with a shallow writing system. Neurophysiological online measures have been shown to be sensitive to orthographic influences on spoken word recognition and provide insights into the time-course of activation and the underlying cognitive mechanisms of orthographic and phonological processing (Perre et al., 2009; Perre & Ziegler, 2008).

Therefore, I tested late German-English bilinguals from Germany in their L1 German and their L2 English, thereby keeping the native language, the educational background, and other potential cultural influences stable while only manipulating the target language. In addition to behavioral measures, I used event-related potentials as an online measure of processing in a shallow writing system, which allows to compare not only whether an effect of orthography can be observed in a transparent orthography, but also whether the time-course of activation is comparable between deep and shallow writing systems. Furthermore, I used time-frequency power (TF power) and ITPC to gain information about the oscillatory characteristics underlying bimodal spoken word processing in deep and shallow orthographies, which provides information about the involved cognitive processes.

In the following, I present two experiments replicating Perre et al.'s (2009) study in German (Experiment 1) and English (Experiment 2). The first experiment aims to answer the question whether an effect of orthography on spoken word processing can be found in German as a shallow writing system and if and how it differs from the effect reported for English, a deep orthography. The second experiment investigates whether late bilinguals with orthographic representations of two languages with different orthographic depths adapt bimodal processing to the target language or whether they transfer native processing mechanisms to their L2. Studies on visual word processing in bilinguals provide evidence for a flexible adaptation of processing mechanisms to the orthographic depth of the target language (e.g., Buetler et al., 2014; Das et al., 2011; Jamal et al., 2012; Kumar, 2014; Nelson et al., 2009). This is for instance evident in different topographical distributions of the same ERP component depending on the linguistic context (German vs. French) in which a word was presented (Buetler et al., 2014). However, the available studies were conducted with early/simultaneous bilinguals, thus, findings for late bilinguals are currently lacking.

In accordance with previous findings, I hypothesize that bimodal spoken word processing should be diminished or absent in German, because due to smaller grain sizes and fewer heterographic homophones, the simultaneous activation of orthography and phonology on the whole word level should not be feasible in a shallow orthography. Moreover, based on findings on the flexible adaptation of processing mechanisms to the orthographic depth of the target language in visual word recognition found for early/simultaneous bilinguals, I suggest that late German-English bilinguals should show comparable results to native speakers when processing English.

2.2 Experiment I

2.2.1 Method

Participants. Twenty-four German native speakers (17 female, seven male; mean age: 23.33 years) without any language impairments were recruited for the reaction time experiment. The data of one additional participant had to be discarded due to being early bilingual. Twenty German native speakers were recruited for the EEG experiment (15 female, five male; mean age: 22.85 years). Participants were right-handed and reported no language impairments nor psychological or neurological deficits. The groups of participants in the reaction time and EEG experiments did not differ in age (*t*(42) = 0.577, *p* = .567).

Material. A set of German stimuli similar to the English stimuli used by Perre et al. (2009) was constructed. However, to expand the pool of stimuli mono- and bisyllabic words were used. The second syllable was always a schwa-syllable. Ninety target words[5] (e.g., *Tee*, Engl. 'tea') were paired with three kinds of primes: phonologically and orthographically related (O+P+, e.g. *See* 'lake' – *Tee*), phonologically but not orthographically related (O-P+, e.g., *Reh* 'deer' – *Tee*) and unrelated (O-P-, e.g., *Lob* 'praise' – *Tee*, see Table A1 in Appendix A for the whole list of critical words). Additionally, 90 pseudoword targets were constructed on the basis of existing mono- and bisyllabic German words by replacing word onsets. The phonotactic rules of German were obeyed. Each pseudoword target was paired with a phonologically related prime (e.g., *Seife* 'soap' – *Geife*) and an unrelated prime (e.g., *Name* 'name' – *Geife*). Note, that the primes were always existing words. Additionally, 300 filler trials were used, half of which contained real word targets and the other half contained pseudoword targets. Word pairs in the filler trials were always unrelated and served to conceal the purpose of the experiment.

Word frequency as well as phonological and orthographic neighborhood size for the critical real word stimuli were taken from the CLEARPOND database (Marian et al., 2012). Mean frequency of target words was 66 per million. Mean frequency of the O-P-, the O-P+ and the O+P+ condition were 24 per million, 20 per million and 15 per million, respectively. Primes were matched across conditions in frequency (*F*(2) = 1.380, *p* = .252), phonological neighborhood size (*F*(2) = 1.315, *p* = .270) and orthographic neighborhood size (*F*(2) = 2.069, *p* = .129). Stimuli were recorded by a female native speaker of standard High German in a soundproof booth via an electret microphone (Sennheiser) and a mixing console (Behringer Xenyx X2442) with the recording software Audacity (Audacity Team, 2019). Sound files were normalized in loudness and edited using PRAAT (Boersma & Weenink, 2020). Each sound file contained 10 ms of silence before onset and after offset of each stimulus to prevent crackling. Stimuli had a mean length of 735 ms. Stimuli were arranged in three different word lists to ensure that each target was presented only once per participant. In each list, each target was paired with a different kind of prime, resulting in 30 critical trials per condition per participant.

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[5] The stimuli 'Bug' (engl. bow) and 'Bowle' (engl.: punch, bowl) were excluded from data analysis post-hoc due to the fact that they are homophones/heterographs with the words 'buk' (engl. baked) and 'Bohle' (engl. plank). It should be noted that the form 'buk' is becoming obsolete in German and is replaced by the regular form 'backte'.

Pseudoword trials were arranged in a similar manner. All filler trials were included in each word list.

Procedure. To reduce artefacts in the EEG, reaction times and neurophysiological data were collected separately.

Reaction times. Participants were tested individually in a quiet, dimly lit room. Stimuli were presented binaurally using OpenSesame presentation software (Mathôt et al., 2012) and a headphone (AKG K240). Participants were instructed to listen to but ignore the prime and decide as fast and as accurately as possible whether the target word was a real German word or a pseudoword. Trials started with the presentation of a fixation dot for 500 ms in the center of the screen, before the prime and target were presented auditorily with an interstimulus interval (ISI) of 20 ms. The fixation dot remained on the screen during presentation of the stimuli. Responses were measured from the onset of the target stimulus. A time-out for responses was set to 3,500 ms. After each response or time-out, a blank screen was presented for 1,500 ms before the initiation of the next trial. Responses were recorded using a response time box (LOBES, version 5/6). No feedback was given during the experiment. The trial scheme can be seen in Figure 7.

EEG. For the EEG experiment, the setting was the same as for the reaction time experiment. Participants were seated at a distance of 80 cm from the monitor and loudspeakers. The task and trial scheme were identical to the reaction time experiment with the exception of the time-out. No time-out was set for responses in the EEG experiment and participants were not instructed to answer as fast as possible to prevent artefacts in the EEG.

Data recording and pre-processing.

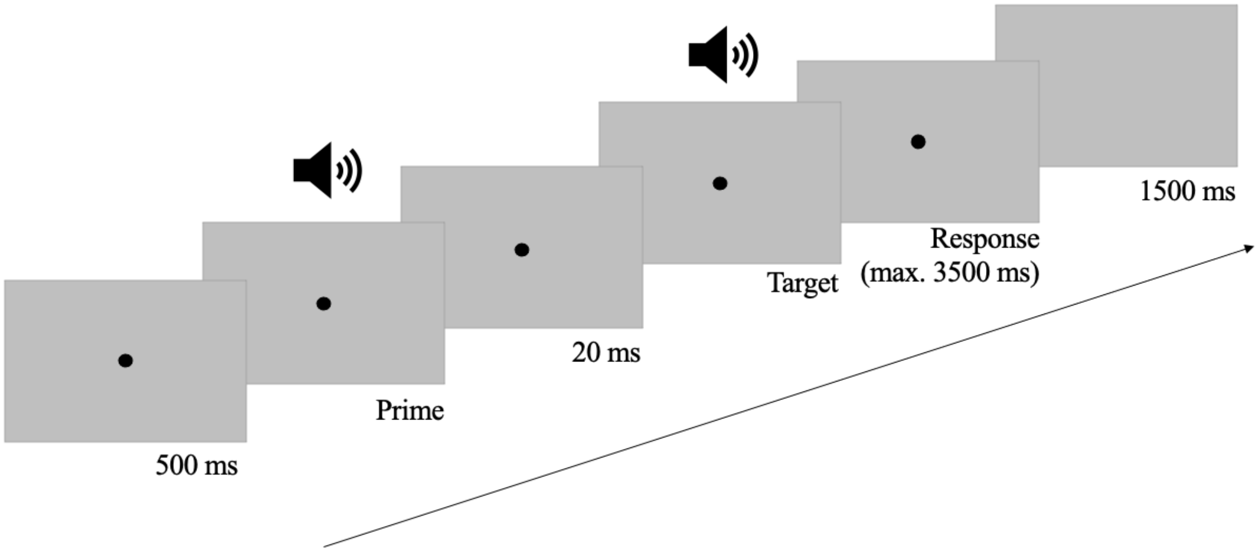
Reaction times. All filler and pseudoword trials were excluded prior to the analysis. Accuracy was coded as a binary dependent variable (correct vs. incorrect). Missing responses due to time-out were classified as incorrectly answered trials.

For analyses of the reaction times, incorrectly answered trials were removed from the data set. This concerned 9.49% of all data points. Reaction times showed a significant right skew according to the D'Agostino test for skewness (skew = 1.448, $z = 19.681$, $p < .001$) and were log-transformed prior to further analysis. As proposed by Baayen and Milin (2010) I forwent *a priori* data-trimming and instead used model criticism to evaluate influential values in the data after transformation. Influential data points were identified by calculating the Cook's Distance

(D_i). This measure calculates the changes in model parameters after deletion of a given data point. The higher the Cook's Distance the higher the probability that the data point is an outlier (Cook & Weisberg, 1980, 1982). None of the data points showed a value higher than $D_i = 1.000$, but some data points exceeded a cut-off value of $D_i < 4/n$, where n denotes the sample size (Cook & Weisberg, 1982). This concerned 1.37% of data points. These data points were excluded prior to further analysis.

Figure 7

Trial scheme of Experiments 1 and 2 on the role of orthography in auditory priming

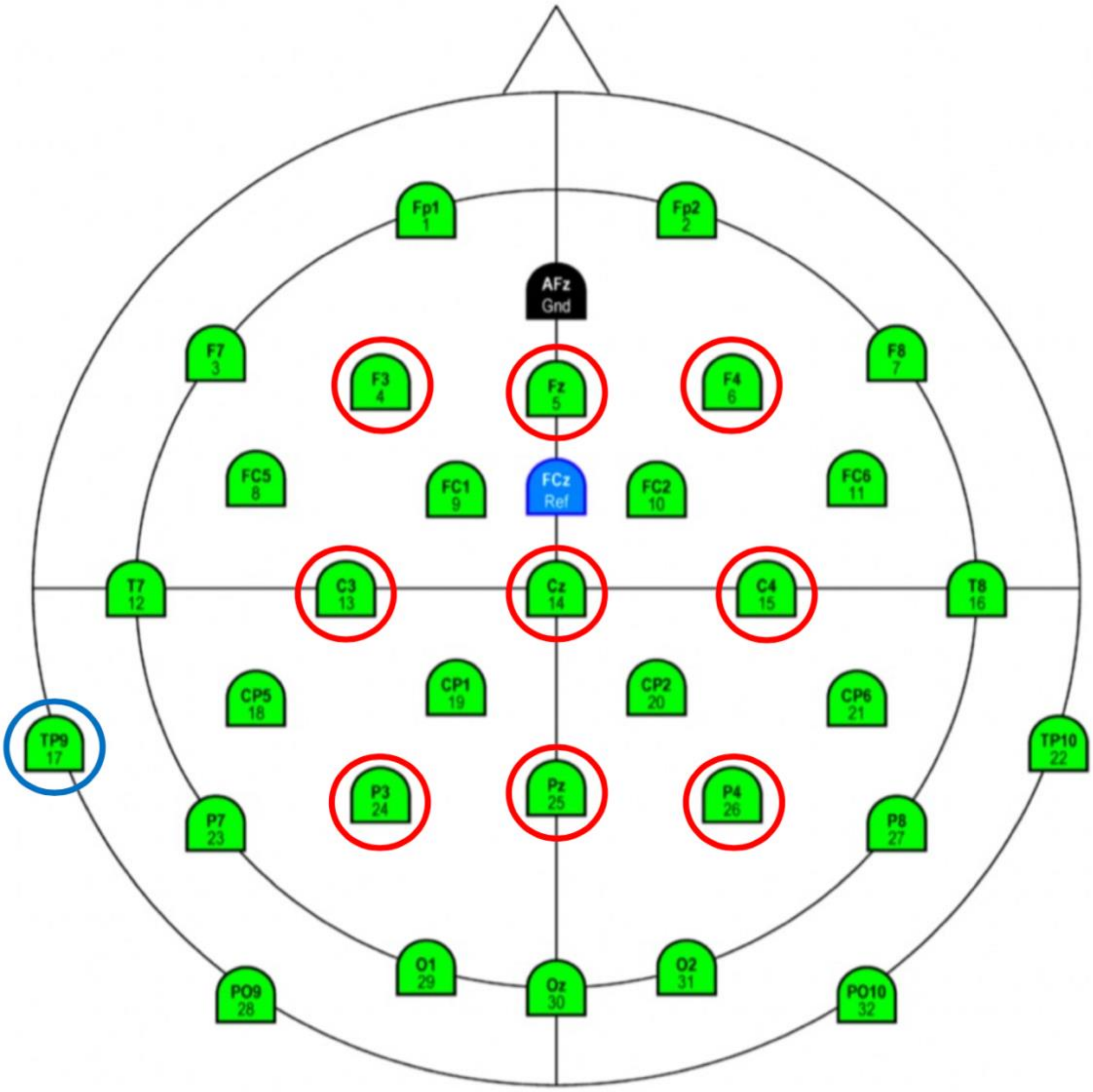


Note. A time-out for responses was only given in the reaction time experiment, but not in the EEG experiment. Other than that, the trial schemes were identical between the two methods.

EEG. The EEG was recorded from 29 active electrodes (actiCAP) placed in an elastic cap (actiCAP) following the 10/20-system at a sampling rate of 500 Hz. Three additional electrodes were placed to the outer canthus of both eyes for monitoring horizontal eye movements as well as below the left eye for monitoring vertical eye movements. Online reference electrode was placed at electrode position FCz. Electrodes were re-referenced offline to the left mastoid electrode (TP9) following the procedure used by Perre et al. (2009). Impedances were kept below 5kΩ (impedances for eye electrodes were kept below 20 kΩ). The BrainAmp Standard Amplifier (BrainVision) was used. Averaging was performed offline. Electrode positions can be seen in Figure 8.

Figure 8

Positions of electrodes of interest according to the standardized 10/20 electrode system for study 1



Note. Gnd = ground electrode, Ref = on-line reference electrode.
Indicated in red are electrodes chosen for EEG analysis. Indicated in blue is the offline reference electrode.

Please note that information and results on ERP data were taken from Türk and Domahs (2022), while time-frequency (TF) analysis was performed separately for this thesis. Therefore, pre-processing differs for the two methods. Pre-processing of the EEG data was performed with the FieldTrip toolbox (Oostenveld et al., 2011) in version 20181231 and the EEGLAB (Delorme & Makeig, 2004) and the ERPLAB toolboxes (Lopez-Calderon & Luck, 2014) for MATLAB (Version 2020a, Version 2023a).

ERPs were calculated offline from correct trials free of ocular and muscular artefacts and time locked to the onset of the target with a pre-stimulus baseline of 100 ms and a post-stimulus epoch of 1175 ms. Prior to calculation of the trials, a baseline correction was performed. Data were filtered using a 0.1 Hz high-pass and a 30 Hz low-pass filter. Artefact rejection was performed automatically with a threshold of 60 µV. Three participants were excluded due to a high level of noise in the data. Thus, data of 17 participants were included in the analyses. In total, 30.20 % of trials were excluded because of noise or incorrect answers. Due to technical issues of the software and our system, a time delay of 114 ms between the EEG trigger and the presentation of the stimulus via loudspeakers was measured. Time locking of the ERPs was corrected for this delay during pre-processing.

As recommended in the literature of EEG/ERP research, I chose the latency and duration of the time windows and regions of interest *a priori* based on Perre et al.'s (2009) study (e.g., Keil et al., 2014; Kilner, 2013; Luck, 2014; Noh & de Sa, 2014). In their study, an effect of orthographic overlap was found in epochs ranging from 400 to 500 ms. This effect was revealed as a significant difference in mean amplitudes between the O+P+ and the O-P+ condition and was localized at frontal and central electrode sites. The O+P+ condition elicited a reduced negativity compared to the O-P+ condition. An effect of phonological overlap was found by Perre et al. (2009) for epochs ranging from 400 to 700 ms as a significant difference in mean amplitudes between the O-P+ and the O-P- condition. A phonological overlap between prime and target elicited a reduced negativity compared to the condition with no overlap. The topographical distribution of this effect was primarily localized at central and parietal electrode sites.

Based on these results, I chose two time windows for analysis, one for each of the expected effects. I predict an effect of orthographic overlap as a significant difference between the O+P+ and the O-P+ condition in a time window from 400 to 500 ms at frontal and central regions of interest, but not at parietal electrode sites. Moreover, I contrasted the O+P+ and the O-P- condition to investigate effects of orthographic and phonological overlap compared to the neutral baseline. Similarly, I expect an effect of phonological overlap in a time window between 400 and 700 ms in form of a significant contrast between the O-P+ and the O-P- condition at central and parietal, but not at frontal regions of interest. The effect of phonological overlap should further be observable between the O+P+ and the O-P- condition as the O+P+ condition shows the same degree of phonological overlap as the O-P+ condition. In addition, I analyzed successive 50 ms epochs in a time window between 300 and 700 ms following the protocol of Perre et al. (2009) to capture the exact time-course of effects in my study.

For TF analysis, data were filtered with a 0.1 Hz high-pass and a 100 Hz low-pass zero-phase FIR filter. Artifacts were first rejected automatically based on EEGLAB's clean_rawdata plugin using Artifact Subspace Removal (ASR). ASR is a non-stationary artifact rejection method based on a principal component analysis (PCA) window and is especially suitable to detect large-amplitude artifacts. ASR can be used to reconstruct the signal in a similar way as independent component analysis (ICA) is used. However, this is only recommended for on-line use of ASR. In offline use, the noisy parts of the data are not reconstructed but excluded. The ASR algorithm uses PCA on successive 500 ms windows of data. Components with large variances relative to clean data sections are detected and excluded from the data. The identification of clean data sections (so-called "calibration data") is performed automatically in EEGLAB and is also based on variance components. While brain signals dedicated to language processing are usually of low variance, artifacts constitute sections with large variances in the data and can thus be identified and excluded based on the ASR algorithm (Chang et al., 2020; Plechawska-Wójcik et al., 2023).

Channels were excluded if they were flat for more than 5 seconds, if they showed amplitudes higher than four times the standard deviation or if they showed poor correlation (less than 0.8) with neighboring channels. None of the channels had to be excluded based on these parameters. Based on ASR, data periods were excluded if they exceeded 20 times the standard deviation of the calibration data. This is a standard and recommended cut-off parameter (Chang et al., 2020; Plechawska-Wójcik et al., 2023). However, for some of the participants, only few trials remained after automatic rejection with this parameter. Therefore, for these participants, the cut-off value was adjusted to 40 or 50 times the standard deviation. According to Chang et al. (2020) any parameter between 10 and 100 times the standard deviation is a suitable value depending on the data. Empirical results show that the optimal ASR parameter is between 10 and 100, as it is small enough to remove activities from artifacts and eye-related components and large enough to retain signals from brain-related components.

After automatic rejection, an independent component analysis (ICA) using the infomax algorithm was performed to detect eye and muscle artifacts that remained in the data after ASR. Running an ICA after ASR is a standard procedure and has been found to reliably detect and remove artifacts (Chang et al., 2020; Plechawska-Wójcik et al., 2023). Afterwards data were checked manually for remaining artefacts and cleaned if necessary. Epoching was performed on cleaned data. The 114 ms delay was considered in the epoching. A central issue for TF analysis is the choice of baseline to which the TF measures in the period of interest are compared. Ideally, the baseline should be as long as the period of interest, as clean as possible (no task- or stimulus-related activity) and as close to the period of interest as possible. Moreover, due to temporal smoothing in TF analyses, the baseline period should end at least

100 ms before onset of the period of interest (Cohen, 2014; Luck, 2014; Morales & Bowers, 2022). However, choosing a long baseline can lead to a higher percentage of artefacts. Luck (2014) suggests that the baseline should be at least 20% of the length of the period of interest.

The choice of baseline was particularly challenging in this paradigm because the period of interest is preceded by the presentation of the prime word, which leads to a high level of non-target related but stimulus-related brain activity in the time period directly prior to target presentation. Thus, a baseline before onset of the prime word had to be chosen. Because prime words were spoken naturally, the length of the stimuli was not controlled. Thus, the longest stimulus was taken as reference which had a duration of 1,177 ms. Thus, the baseline was chosen to be 2,100 to 1,700 ms before onset of the target, which represented the inter-trial interval (ITI) for all trials, regardless of stimulus length (see also Figure 7). However, this meant that the epochs had to be very long with a pre-stimulus interval of 2,100 ms and a post-stimulus interval of 1,175 ms. Because participants tend to blink during the ITI, this resulted in a high level of noise. Only correctly answered epochs were considered for further analysis. Rejection rates, thus, included rejection based on incorrect answers and noise. On average 27.36% (*SD* = 15.08%) of trials were rejected. Individual rejection rates ranged from 7.78% to 55.56%. One participant was excluded, because so little trials were retained after artefact rejection that there were no trials left for some of the conditions.

TF analysis was performed using EEGLAB following the suggestions of Morales and Bowers (2022). TF power and ITPC measures were calculated. TF decomposition was performed with a complex morlet wavelet ranging from three to 10 cycles. The number of cycles determines the time-frequency resolution. Fewer cycles were used at low frequencies to increase temporal precision at lower frequency bands and cycles were gradually increased as frequency increased to enhance frequency precision at higher frequencies (see Morales & Bowers, 2022). The lowest frequency that can be analyzed is restricted by the length of the time window. Specifically, Cohen (2014) recommends that the data to be analyzed should have at least three full cycles of the lowest frequency for analysis. If low frequencies like delta are of interest, the epochs need to be long enough to contain a few cycles at that frequency (Cohen, 2014; Morales & Bowers, 2022). However, as stated above, the length of the epoch is related to the amount of noise in the data. The longer the epoch the higher the probability that it will contain an artifact and be rejected. Given that the post-stimulus epoch in this study ranges from 0 to 1.175 seconds, the lowest frequency that can be analyzed is 3 Hz. The highest frequency that can be analyzed is technically limited by the Nyqist frequency (1/2 the sample rate). Because the sampling rate in this study was 500 Hz, the highest frequency that can be recovered from the signal is 250 Hz. However, Cohen (2014) suggests that the sampling rate should be more than twice as high as the highest frequency of interest because having more data points per oscillation cycle increases the signal-to-noise ratio and allows for better estimation of high-frequency activity, especially if phase coherence is of interest. I analyzed up to a frequency of 80 Hz which corresponds to the lower gamma range (Cohen, 2014). Consequently, all frequency bands connected to cognitive-linguistic processing are included in the data. Restricting the analysis to specific frequency bands of interest is preferable to reduce the number of statistical tests. However, because no *a priori* assumptions can be made for this study, I analyzed frequencies between 3 and 80 Hz at a resolution of 0.5 Hz increments as suggested by Morales and Bowers (2022). Frequencies were then combined to frequency bands in the following way: delta (< 5 Hz), theta (5-8 Hz), alpha (8-12 Hz), beta (15-30 Hz) and gamma (30-80 Hz). TF decomposition is susceptible to different trial numbers in different conditions which can affect resolution. Therefore, subsampling was used to draw 10 trials for 9 subsamples of data. This assured equal resolution across conditions while ensuring that all available data was sampled once (see Morales & Bowers, 2022).

Data analysis.

Behavioral data. Statistical analysis was performed with R Studio and the lme4 package (Bates et al., 2015). Post-hoc tests and effect size estimates for contrasts were calculated using the emmeans package (Lenth et al., 2021). Effect size estimates for mixed model predictors were calculated using the MuMIn package (Bartón, 2020). Accuracy data were analyzed using a mixed effects logistic regression model with condition (O+P+, O-P+, O-P-) as a fixed effect and by-subject and by-item random intercepts. Reaction times were analyzed with a linear mixed effects model with condition as a fixed effect and by-subject and by-item random intercepts. Significance of the fixed effect was tested with a Type II Wald-Chi-Square test and the Kenward-Rogers approximation of degrees of freedom. The Kenward-Rogers approximation has been found to be preferable over other methods of significance testing in mixed-effects models, especially for small sample sizes and a small number of items (Luke, 2017). For post-hoc tests, multiple comparisons were made between all factor levels of the factor condition and Bonferroni correction was applied to control for family wise error rates. The test statistic, p value and effect size (R^2, d)[6] for significant results are reported.

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[6] For mixed model predictors, marginal R^2 is reported as defined by Nakagawa & Schielzeth (2013). This effect size gives only the variance component explained by the fixed factor of interest.

ERP data. I used a linear mixed effects model for each of the two time windows on single-trial data. Analyses were performed for three frontal (F3, Fz, F4), three central (C3, Cz, C4) and three parietal (P3, Pz, P4) electrodes. Electrode positions are indicated in Figure 8. The model included condition (O+P+, O-P+, O-P-), anterior-posterior distribution (frontal, central, parietal) and lateralization (left, midline, right) as fixed effects and by-subject and by-item random intercepts. Interaction terms between condition and anterior-posterior distribution and condition and lateralization were included in the model. Significance of the fixed effects was tested with a Type II Wald-Chi-Square test and the Kenward-Rogers approximation of degrees of freedom. For post-hoc tests, I used planned *t*-tests to compare the relevant contrasts in each time window: In the first time window (400–500 ms), in which I expected an effect of orthographic overlap, the O+P+ and the O-P+ conditions and the O+P+ and the O-P- conditions were contrasted. In the phonological time window (400–700 ms), in which I expected an effect of phonological overlap, the O-P+ and O-P- as well as the O+P+ and O-P- condition were compared. Bonferroni correction was applied to account for family wise error rates.

Additionally, I analyzed the data by comparing the effects in successive 50 ms epochs in a time window between 300 and 700 ms. I used a linear mixed effects model with condition (O+P+, O-P+, O-P-), anterior-posterior distribution (frontal, central, parietal), lateralization (left, midline, right) and epoch (300–350 ms, 350–400 ms, 400–450 ms, 450–500 ms, 500–550 ms, 550–600 ms, 600–650 ms, 650–700 ms) as fixed effects and by-subject and by-item random intercepts. Interaction terms between condition, anterior-posterior distribution, lateralization, and epoch were also included in the model. Bonferroni correction was applied to post-hoc comparisons to adjust for family wise error rates. The investigated contrasts were similar to those in the *a priori* analysis. The test statistic, *p* value and effect size (R^2, *d*) for significant results are reported.

TF measures. TF measures were analyzed in a similar way as ERPs. Because no clear hypotheses can be formed for the TF analysis, this has to be considered an exploratory analysis. However, analysis was restricted to the two time-windows and the regions of interest (ROIs) of the confirmatory ERP analysis to reduce the number of statistical tests. The goal of the TF analysis is to get more information about the cognitive mechanisms underlying the processing of orthographic information during spoken word recognition as measured by ERPs. Thus, it makes sense to restrict TF analyses to the temporal and spatial distributions of the confirmatory ERP analysis. A linear mixed effects model with the fixed factors condition (O+P+, O-P+, O-P-), anterior-posterior distribution (frontal, central, parietal), lateralization (left, midline, right) and frequency band (delta, theta, alpha, beta, gamma) and by-subject random intercepts was computed. Note that TF measures were not computed on a trial-by-trial basis, thus by-item random intercepts were not included in the model. A separate model was calculated for each time window. Post-hoc tests for condition were performed in a similar manner as stated above for the confirmatory ERP analysis. Contrasts were tested against the normal distribution with asymptotic degrees of freedom. Testing against the *t*-distribution with Kenward-Rogers approximation of degrees of freedom is suggested for small sample sizes and can lead to more accurate estimates (Luke, 2017). However, this method becomes not feasible with a high number of observations due to steep increases in processing time. Testing against the normal distribution with asymptotic degrees of freedom resulted in only minor differences in the decimal part of the estimate, while *p* values and the corresponding conclusions were identical irrespective of the method. Bonferroni correction was applied to account for family-wise error rates. The respective test statistic, *p* value and effect size for significant results are reported.

Table 5

Descriptive summary of behavioral measures of Experiment 1 on the role of orthography in auditory priming

Condition	**Accuracy**		**Reaction Times**				
				raw RTs (in ms)		log RTs	
	n	*M*	*n*	*M*	*SD*	*M*	*SD*
O+P+	711	0.921	643	767.081	147.426	-282.754	186.330
O-P+	705	0.914	637	775.681	156.373	-273.529	196.830
O-P-	712	0.881	620	891.819	172.719	-132.252	187.023

Note. Accuracy equals the proportion of correctly answered trials of all critical real word trials in the respective condition. *n* = number of trials.

2.2.2 Results

2.2.2.1 Behavioral results. Accuracy data showed a significant effect of condition ($W(2) = 10.414$, $p = .006$, $R^2 = .010$). Post-hoc tests revealed that accuracy was significantly higher in the O+P+ condition than in the O-P- condition ($z = 2.994$, $p = .008$, $d = 0.651$) and marginally higher in the O-P+ than in the O-P- condition ($z = 2.382$, $p = .052$, $d = 0.508$). The contrast between O+P+ and O-P+ was not significant ($z < 1$, $p = 1.000$). Reaction times also revealed a significant effect of condition ($W(2) = 486.260$, $p < .001$, $R^2 = .114$). Post-hoc tests showed significant differences between the O+P+ and the O-P- ($t(1791) = -19.507$, $p < .001$, $d = 1.106$) and between the O-P+ and O-P- condition ($t(1793) = -17.985$, $p < .001$, $d = 1.023$), but not between the O+P+ and O-P+ condition ($t(1792) = -1.467$, $p = .428$). Table 5 shows a summary of descriptive measures for the behavioral data of Experiment 1.

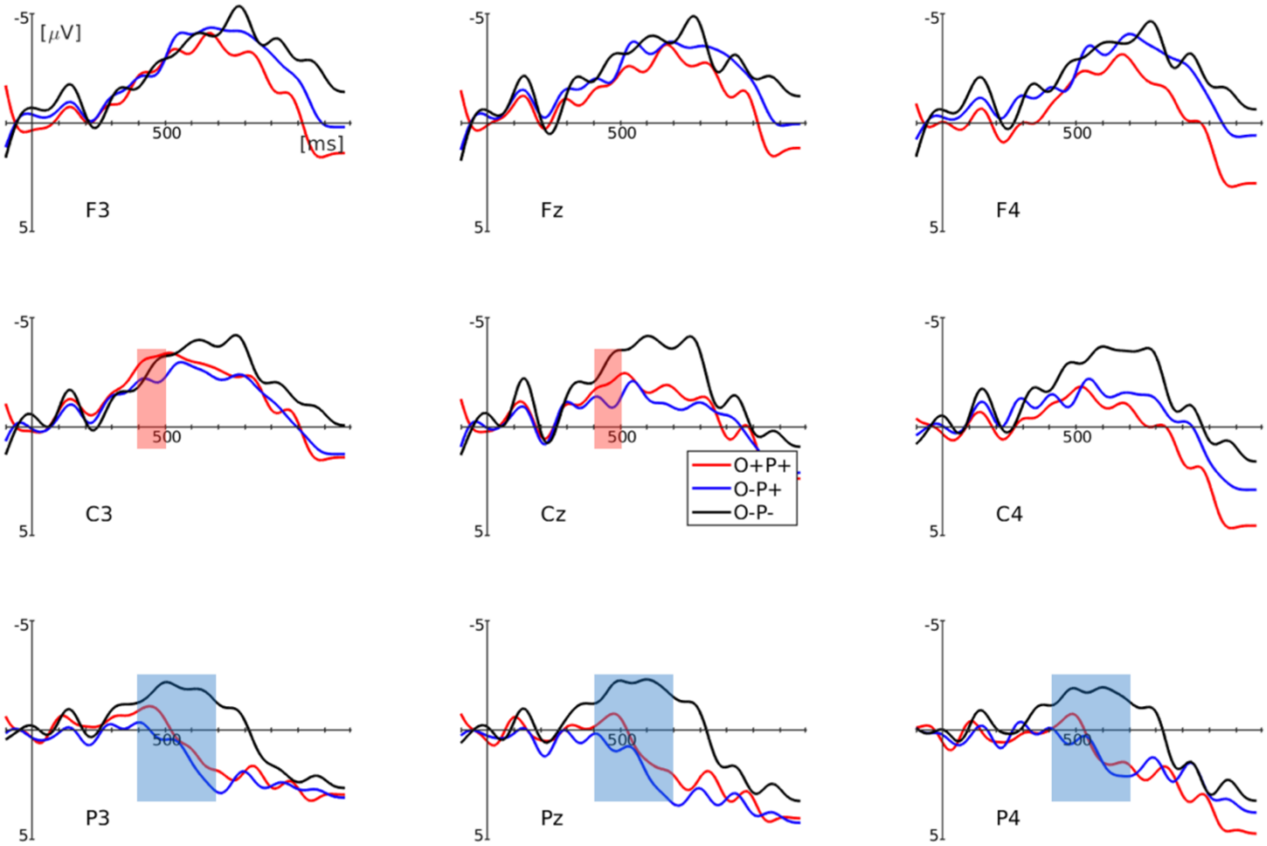
2.2.2.2 ERP results.

Confirmatory analysis. For the orthographic time window, results showed a main effect of condition ($W(2) = 20.555$, $p < .001$, $R^2 = 0.002$) and a main effect of anterior-posterior distribution ($W(2) = 45.607$, $p < .001$, $R^2 = 0.004$). The main effect of lateralization ($W(2) = 4.926$, $p = .085$, $R^2 < 0.001$) and the interaction between condition and anterior-posterior distribution ($W(4) = 7.946$, $p = .094$, $R^2 = 0.007$) showed a tendency towards significance but did not reach the conventional significance level. The interaction between condition and lateralization ($W(4) = 2.859$, $p = .582$) did not reach significance. The planned *t*-test between the O+P+ and the O-P+ condition revealed a significant difference in mean amplitudes ($t(9581) = -2.641$, $p = .017$, $d = -0.068$). The direction of the effects showed a more negative-going wave for the condition with orthographic overlap (O+P+) compared to the condition with only phonological overlap (O-P+). The contrast between the O+P+ and the O-P- condition revealed no significant differences ($t(9577) = 1.863$, $p = .125$).

For the phonological time window, a main effect of condition ($W(2) = 39.936$, $p <. 001$, $R^2 = 0.004$) and a main effect of anterior-posterior distribution ($W(2) = 161.874$, $p < .001$, $R^2 = 0.015$) was found. The main effect of lateralization ($W(2) = 4.428$, $p = .123$) and the interaction between condition and lateralization ($W(4) = 2.782$, $p = .620$) did not reach significance. Importantly, the interaction between condition and anterior-posterior distribution was significant ($W(4) = 26.662$, $p < .001$, $R^2 = 0.021$). Subsequent analyses showed that the interaction arose because conditions differed at central and parietal electrode sites ($W(2) = 58.522$, $p < .001$, $R^2 = 0.009$), but not at frontal electrode sites ($W(2) < 1$, $p = .911$). Planned *t*-tests showed a significant difference between the O-P+ and O-P- condition ($t(6382) = 7.459$, $p < .001$, $d = 0.234$) and between the O+P+ and O-P- condition ($t(6374) = 5.152$, $p < .001$, $d = 0.161$). Here, the unrelated condition (O-P-) showed a more negative-going wave compared to both conditions with phonological overlap (O+P+ and O-P+). Grand-average ERPs are plotted in Figure 9.

Figure 9

Grand-average ERPs over nine electrodes of Experiment 1 on the role of orthography in auditory priming



Note. Negativities are plotted upwards. The orthographic priming effect (O+P+ compared to O-P+ and O-P-, 400-500 ms) is marked with a red box, the phonological priming effect (O-P+ and O+P+ compared to O-P-, 400-700 ms) is marked with a blue box. An 8 Hz lowpass filter was applied to the ERP plot for better visualization.

Analysis of successive 50 ms epochs. The exploratory analysis of successive 50 ms time windows revealed significant main effects for all fixed factors ($W(2) > 24.714$, $p < .001$, $R^2 = 0.001\text{-}0.007$) and significant interaction effects between condition and epoch ($W(14) = 63.385$, $p < .001$, $R^2 = 0.004$), condition and anterior-posterior distribution ($W(4) = 100.082$, $p < .001$, $R^2 = 0.011$) and condition and lateralization ($W(4) = 15.606$, $p = .004$, $R^2 = 0.002$). The three-way interaction between condition, anterior-posterior distribution and epoch did not reach significance ($W(28) = 33.771$, $p = .209$). Results from post-hoc analyses are presented in Table 6. The effect of orthographic overlap was restricted to an epoch between 450 and 500 ms and did not show a specific distribution as no interaction with anterior-posterior distribution was observed. The effect of phonological overlap was evident in an early epoch of 300 to 350 ms and then in consecutive epochs from 450 to 700 ms. While the effect was broadly distributed in the earlier epochs, it showed a localization at central and parietal electrode sites in the greater part of the N400 component.

Table 6

Results of post-hoc analyses in consecutive 50 ms epochs between 300 and 700 ms at three regions of interest for Experiment 1 on the role of orthography in auditory priming

	Orthographic priming effect			**Phonological priming effect**		
Epoch (ms)	frontal	central	parietal	frontal	central	parietal
300-350	-	-	-	< .05	< .05	< .05
350-400	-	-	-	-	-	-
400-450	-	-	-	-	-	-
450-500	< .01	< .01	< .01	< .001	< .001	< .001
500-550	-	-	-	-	-	< .001
550-600	-	-	-	-	< .001	< .001
600-650	-	-	-	-	< .01	< .001
650-700	-	-	-	-	< .001	< .001

Note. From “Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language” by S. Türk and U. Domahs, 2022, *Brain and Language, 235*, 105186, p. 6 (https://doi.org/10.1016/j.bandl.2022.105186). Copyright 2022 by Elsevier.

2.2.2.3 TF results.

The following table gives an overview of all TF effects found for Experiment 1 on the role of orthography in auditory priming. A comprehensive description of all statistical results can be found in Appendix B.

Table 7

Overview of TF results of Experiment 1 on the role of orthography in auditory priming

Orthographic time window			
	Power		
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O+P+ > O-P+, O-P-	delta	frontal central parietal	left, midline, right right left, midline, right
O+P+ > O-P-	delta	central	left, midline
O+P+ > O-P+, O-P-	theta	frontal	left, midline, right
O+P+ > O-P+	theta	central	left, right

		parietal	left, midline, right
O+P+ > O-P+ O+P+ < O-P-	alpha	frontal central	left, midline, right left, midline, right
O+P+ < O-P+, O-P-	alpha	parietal	left, midline, right
O+P+ > O-P+, O-P-	beta	frontal	left, midline
O+P+ > O-P+ O+P+ < O-P-	beta	frontal central parietal	right left, midline, right left, midline, right
O+P+ < O-P+, O-P-	gamma	frontal central parietal	left (P+)/right (P-) left, midline left, midline, right
O+P+ > O-P+, O-P-	gamma	central	right
		ITPC	
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O+P+ > O-P+	delta	frontal	left
O+P+ < O-P-	delta	parietal	right
O+P+ > O-P+	theta	frontal central	left left, midline
O+P+ > O-P+, O-P-	theta	frontal	right
O+P+ > O-P+	alpha	frontal central parietal	left, midline, right left left
O+P+ < O-P-	alpha	parietal	midline
O+P+ < O-P+, O-P-	alpha	parietal	right
O+P+ > O-P+, O-P-	beta	frontal central	left, midline, right left, midline
O+P+ > O-P+	beta	central	right
O+P+ < O-P-	gamma	frontal	left
O+P+ > O-P+	gamma	frontal central parietal	left, midline left, midline, right left, midline
O+P+ > O-P+, O-P-	gamma	frontal parietal	right right
		Phonological time window	
		Power	

Effect	Frequency band	Anterior-posterior distribution	Lateralization
O-P- < O-P+, O+P+	delta	frontal	left, midline, right
		central	left
		parietal	left, midline, right
O-P- < O+P+	delta	central	midline, right
O-P- > O+P+	theta	central	left
O-P- > O-P+	theta	central	right
O-P- > O-P+, O+P+	alpha	frontal	left, midline, right
		central	left, midline, right
		parietal	left, midline, right
O-P- < O+P+	beta	frontal	left
O-P- > O-P+	beta	frontal	midline, right
O-P- > O-P+, O+P+	beta	central	left, midline, right
		parietal	left, midline, right
O-P- > O-P+, O+P+	gamma	frontal	right
O-P- > O+P+	gamma	central	left, midline
		parietal	midline, right
O-P- < O-P+	gamma	parietal	left

ITPC

Effect	Frequency band	Anterior-posterior distribution	Lateralization
O-P- > O-P+	delta	frontal	midline, right
O-P- > O+P+	delta	central	right
O-P- > O-P+	theta	frontal	left, midline, right
		central	left, midline
		parietal	left
O-P- < O+P+	theta	parietal	midline, right
O-P- > O-P+	alpha	frontal	left, midline, right
		central	left, midline
		parietal	left
O-P- > O-P+, O+P+	alpha	central	right
		parietal	midline
O-P- > O+P+	alpha	parietal	right
O-P- > O-P+	beta	frontal	left, midline
O-P- < O+P+	beta	frontal	midline
		central	left, right
O-P- < O-P+	beta	parietal	left, right
O-P- < O-P+, O+P+	beta	frontal	right
		parietal	midline

O-P- > O-P+, O+P+	gamma	frontal central parietal	left, midline left, midline left
O-P- > O-P+	gamma	frontal central parietal	right right midline, right

Note. O+P+ = orthographically and phonologically related, O-P+ = phonologically related, O-P- = unrelated.

2.2.3 Summary

The aim of Experiment 1 was to investigate whether orthographic influences on spoken word recognition as previously reported for English and French generalize to a language with a shallow orthography. German native speakers were tested on German spoken words with behavioral and neurophysiological measures. Both conditions with phonological overlap (O+P+, O-P+) produced significantly higher accuracies and lower reaction times compared to the unrelated condition. Descriptive statistics show higher accuracies and lower reaction times for the O+P+ compared to the O-P+ condition, which illustrates an additive effect of orthographic overlap on top of the phonological overlap. However, these differences were not significant.

The ERP data showed an effect of phonological overlap in an *a priori* chosen time window of 400 to 700 ms that became apparent as a significantly reduced N400 amplitude for the phonological overlap conditions (O+P+, O-P+) compared to the unrelated condition (O-P-). An interaction with anterior-posterior distribution was significant, which indicates that this effect was restricted to central and parietal electrode positions and, thus, showed a comparable distribution as the results in Perre et al.'s (2009) study. The time course revealed a significant effect of phonological overlap in an epoch from 300 to 350 ms and from 450 to 500 ms that was not restricted to specific regions of interest. In subsequent epochs from 500 to 700 ms, the effect of phonological overlap was restricted to central and parietal electrode sites. Hence, the phonological effect closely resembled the results found for English native speakers.

A significant difference in N400 amplitude for orthographic and phonological overlap (O+P+) compared to phonological overlap (O-P+) was found in an *a priori* analysis of a time window of 400 to 500 ms. Strikingly, the N400 amplitude of the O+P+ condition was higher than that of the O-P+ condition indicating stronger facilitation for primes that did not share orthographic features with the target. No difference was found for the orthographic and phonological overlap condition (O+P+) compared to the unrelated condition (O-P-). A closer look at the time course by analyzing consecutive 50 ms epochs revealed that the orthographic effect was significant in an epoch ranging from 450 to 500 ms. An interaction with anterior-posterior distribution was not observed, thus, contrary to results found by Perre and colleagues

(2009) a specific localization of the effect could not be detected in the German study. The effect seemed to be more broadly distributed than the effect observed by Perre and colleagues. These results indicate that differences between languages were restricted to the orthographic effect. In the German study, the condition with only phonological overlap (O-P+) showed a significantly reduced negativity compared to the condition with orthographic and phonological overlap (O+P+). This pattern of results suggests that orthographic overlap counteracts facilitation of phonologically identical rimes. In the study by Perre et al. (2009), orthographic and phonological overlap (O+P+) showed stronger facilitation compared to the condition with only phonological overlap (O-P+) in the orthographic time window.

TF analysis showed overall higher power for the O-P- condition compared to the conditions with phonological overlap in the theta, alpha, beta and gamma bands. Reduced power for the O-P- condition compared to O-P+ and O+P+ was found in the delta band. However, for the beta and gamma band some inconsistent results remained that indicated a power reduction for the unprimed condition compared to the primed conditions. ITPC was found to be higher for the O-P- compared to both conditions with phonological overlap in the delta, theta, alpha and gamma band. Reduced ITPC was found for the beta band. This is in line with previous studies on phonological priming reporting reduced power and phase synchronization in the gamma band for the primed condition compared to the unprimed condition due to repetition suppression (Matsumoto & Iidaka, 2008; Wen et al., 2018). Repetition suppression refers to the decrease of neural activity for items that are presented repeatedly over a short period of time (Nordt et al., 2016). These effects were found in similar time windows as in the current study. Unfortunately, these studies limited analysis to the gamma band, consequently, it is unknown whether effects were present in other frequency bands. However, beta band desynchronization has been associated with expectation violations, i.e., with the interruption of a current cognitive state by novel and unexpected stimuli (Weiss & Mueller, 2012). Hence, the decrease in ITPC in the beta band for the unprimed condition indicates an interruption of the cognitive state and a violation of expectations. A decrease in power for the O-P- condition in this frequency band should also have been observed, however, an increase was found instead. Activation in the alpha band has been connected to attentional processes. Alpha band synchronization, that is higher power and higher phase coherence, has been connected to inhibitory processes in reaction to irrelevant and possibly distracting stimuli (Foxe & Snyder, 2011; Klimesch, 2012). Thus, alpha band desynchronization in relation to the O-P+ and O+P+ condition could reflect higher attention for phonologically related target words. The theta band has been associated with lexical-semantic access (Bastiaansen et al., 2005).

Reduced power and ITPC for the O-P+ and the O+P+ conditions compared to the O-P- condition might, thus, indicate facilitated lexical access for targets following related prime words relative to unrelated prime words. It should be noted, however, that this effect was most prominent for the O-P+ compared to the O-P- condition and less so for the O+P+ compared to the O-P- condition. This indicates that facilitation to lexical access was mostly limited to the priming conditions without orthographic overlap. Delta band activity has been associated with complexity and mental effort, showing increased power and ITPC in this frequency band for higher task complexity (Bizas et al., 1999), higher listening effort (Mohammadi et al., 2023) and ungrammaticality and conflict (Roehm et al., 2003). Increases in delta power and ITPC have been observed for engagement in mental tasks and have been associated with inhibition of the sensory afferences that interfere with internal concentration and inhibition of the "default mode network" (Dimitriadis et al., 2010; Harmony, 2013). Thus, delta band increases for the O-P+ and the O+P+ conditions relative to the O-P- condition might indicate higher concentration and cognitive engagement for conditions with phonological overlap.

For orthographic priming, too, some inconsistencies in the TF analysis remained. However, an overall pattern emerged that revealed higher power for the O+P+ condition compared to the O-P+ and the O-P- conditions in the delta, theta and beta bands. In the alpha band, power was higher for the O+P+ compared to the O-P+ condition at frontal and central electrode sites but reduced compared to the O-P- condition. Reduced power for the O+P+ condition compared to the other conditions was also found in the gamma band. ITPC was higher for the O+P+ compared to the other two conditions in the theta and beta bands. In the delta, alpha and gamma band, ITPC was overall higher for the O+P+ compared to the O-P+ condition but reduced compared to the O-P- condition. These findings are overall in line with the ERP results and with the findings on the phonological priming effect. Reduced activity in the delta and beta band for the O-P+ and the O-P- conditions compared to the O+P+ condition is indicative of orthographic priming. Delta band desynchronization reflects less cognitive engagement with unprimed conditions. Beta band desynchronization shows higher expectation violations when a prime was followed by a target that did not show orthographic overlap. Theta band desynchronization for the O-P+ and the O-P- compared to the O+P+ condition might indicate easier lexical access for the former two conditions and, thus, lateral lexical inhibition for the O+P+ condition. This was especially pronounced compared to the O-P+ condition and less so compared to the O-P- condition. The alpha and gamma band are especially interesting, because they show the exact same pattern as revealed by ERPs: Alpha band desynchronization for the O-P+ condition compared to the O+P+ condition, but higher alpha power and ITPC for

O-P- compared to O+P+. A similar pattern was found in the gamma band. This shows that orthographic overlap led to stronger inhibition and a reduced repetition suppression for the O+P+ condition compared to the condition without orthographic overlap. Because alpha activity is also connected to sensory information, this might be specifically associated with the inhibition of the written modality in favor of the spoken modality or, as Foxe and Snyder (2011, p. 2) state, "the anticipatory suppression of one modality in favor of another". However, the O+P+ condition still produced higher attention and repetition suppression than the unprimed condition. These findings might indicate that the ERP results observed in the German study, specifically the higher N400 amplitude for the O+P+ compared to the O-P+ condition, might be driven by inhibitory processes in the theta, alpha and gamma frequency ranges.

In contrast to the findings in English presented by Perre et al. (2009), orthographic overlap does not facilitate the processing of the target in German but seems to counteract the facilitation found for the phonological rime such that processing of the target in the O+P+ condition becomes equal to the neutral baseline. This is driven by inhibitory processes in the theta, alpha and gamma frequency ranges. I, therefore, conclude that orthography influences spoken word processing in German, but in a reverse direction than previously observed by Perre and colleagues for native English speakers: orthographic and phonological overlap in the German study (O+P+) results in higher N400 amplitudes compared to only phonological overlap (O-P+). The orthographic overlap, therefore, seems to reduce facilitation of phonological overlap during spoken word processing for native speakers of shallow orthographies. In the second experiment, I investigated whether this also holds for German-English late bilinguals when processing English as an L2.

2.3 Experiment II

2.3.1 Method

Participants. Twenty-five German-English late bilinguals (20 female, four male, one divers; mean age: 23.88 years) without any language impairments were recruited for the reaction time experiment and 28 were recruited for the EEG experiment. Of the latter, three were excluded due to technical issues, four were excluded due to psychological or neurological deficits and one was excluded for being bilingual. All of the remaining 20 participants (14 female, six male; mean age: 25.6 years) were right-handed late German-English bilinguals without language impairments and no psychological or neurological deficits.

Participants were given a self-judgement language questionnaire that assessed English language skills on a four-point rating scale (*beginner (1)*, *intermediate (2)*, *advanced (3)*, *native-*

like (4)) in the following domains: oral speech production, listening comprehension, written speech production, reading comprehension and overall language competency. Moreover, time spent in an English-speaking country (excluding holidays) and age of acquisition were assessed. For the reaction time experiment, participants rated their language skills to be "advanced" with a mean of 3.15 and had spent on average 3.04 months in an English-speaking country. Mean age of acquisition was 9.96 years. For the EEG experiment, participants' language skills were rated slightly higher with a mean of 3.80. They had spent an average of 6.90 months in an English-speaking country and reported a mean age of acquisition of 9.70 years. Detailed results of the language questionnaire in the two experiments are shown in Table 8. Based on these results, the bilinguals have a high proficiency in English as a second language.

Participants in the RT and EEG groups did not significantly differ with regard to age ($t(43) = -1.227$, $p = .227$), self-rated language skills ($t(43) = 0.698$, $p = .489$), time spent in an English-speaking country ($t(24.713) = -1.486$, $p = .169$) or age of acquisition ($t(43) = 0.356$, $p = .724$).

Material. Stimuli for the English experiment were taken from the stimulus list provided by Perre et al. (2009). Targets consisted of 90 monosyllabic English words paired with primes in three different conditions: orthographically and phonologically similar rime (O+P+, e.g., *beef* - *reef*), phonologically but not orthographically similar rime (O-P+, e.g., *leaf* - *reef*) and unrelated (O-P-, e.g., *sick* - *reef*). The authors indicated that the primes were matched in frequency as well as in number of phonological neighbors.

However, Perre et al. (2009) took Kučera and Francis (1967) for reference, which made it impossible to compare the English stimuli of Experiment 2 with the German stimuli of Experiment 1. I, therefore, calculated frequency values as well as phonological and orthographic neighborhood sizes using the CLEARPOND database (Marian et al., 2012). This database allows cross-linguistic comparisons between five different languages including English and German and is based on the SUBTLEX-US (Brysbaert & New, 2009) and the SUBTLEX-DE (Brysbaert et al., 2011) corpora, respectively. Perre et al. (2009) reported a mean word frequency of 26 per million for the target words and of 63.0, 65.7 and 61.6 per million for the O-P-, O-P+ and O+P+ conditions, respectively, based on Kučera and Francis (1967). According to CLEARPOND, frequency of target words was 41 per million and 88.7, 110.8, and 69.2 per million for the O-P-, O-P+ and O+P+ conditions, respectively. Prime words did not differ in frequency ($F(2) = 1.099$, $p = .334$) nor in phonological neighborhood size ($F(2) = 1.642$, $p = .196$), but did differ in orthographic neighborhood size ($F(2) = 15.717$, $p < .001$)

according to the CLEARPOND database. The O-P+ condition showed a significantly lower number of orthographic neighbors than the O+P+ ($t(169.726) = -4.332$, $p < .001$) and the O-P- condition ($t(166.162) = -5.520$, $p < .001$).

German stimuli of Experiment 1 and English stimuli of Experiment 2 differed in prime frequency ($t(273.233) = -3.773$, $p < .001$) as well as in phonological ($t(500.941) = -11.237$, $p < .001$) and orthographic ($t(444.341) = -9.534$, $p < .001$) neighborhood sizes. English prime words were more frequent and had a higher number of phonological and orthographic neighbors than German prime words. I calculated the Levenshtein Distance between the rime of the target and the rime of the O-P+ prime to measure the orthographic distance between them. The Levenshtein Distance is the minimal number of operations (addition, deletion, or substitution) needed to transform one string of letters into another (Kruskal, 1983; Levenshtein, 1966). Mean Levenshtein Distance was 1.84 for English and 1.11 for German, this difference was significant ($t(123.095) = 6.769$, $p < .001$) indicating that the orthographic distance between O-P+ prime and target was higher in English than in German. These differences between German and English stimuli can be explained on the basis of the orthographic depth, because by definition, words with orthographic inconsistencies occur much more frequently and show greater inconsistencies in languages with a deep orthography.

The stimulus list provided by the authors contained only real word stimuli. Therefore, I constructed 90 pseudo-word targets with two kinds of primes: phonologically similar rime (e.g., *time* - *sime*) and unrelated (e.g., *drake* - *crame*). Note that the primes were always real words. Pseudo-words were created by taking real monosyllabic English words and replacing word onsets. The phonotactic rules of English were obeyed. An English native speaker reviewed the pseudo-word list to ensure that all constructed items were indeed non-existent in English. Additionally, 300 non-related word pairs were constructed as filler trials. Half of the filler trials contained a real word target and the other half contained pseudo-word targets.

Stimuli were recorded by a female native speaker of American English in a soundproof booth via an electret microphone (Sennheiser) and a mixing console (Behringer Xenyx X2442) with the recording software Audacity (Audacity Team, 2019). Sound files were normalized in loudness and edited using PRAAT (Boersma & Weenink, 2020). Each sound file contained 10 ms of silence before onset and after offset of each stimulus to prevent crackling. Stimuli had a mean length of 613 ms.

Again, three word lists were created in the same way as in Experiment 1.

Procedure. The procedures for both the reaction time and the EEG experiments were identical to Experiment 1.

Data recording and pre-processing.

Behavioral data. Data pre-processing was identical to Experiment 1. Again, incorrectly answered trials were excluded prior to the analysis of reaction time data. This concerned 17.28% of all data points. Reaction times showed a significant right skew according to the D'Agostino test for skewness (skew = 2.622, $z = 27.269$, $p < .001$) and were log-transformed before further analysis to account for the non-normality of the data. All data points showed a Cook's Distance lower than $D_i = 1.000$. However, some exceeded a cut-off value of $D_i < 4/n$. This concerned 2.323% of all data points. These data points were excluded prior to further analysis.

EEG data. Recording of the EEG signal and pre-processing of the data were identical to Experiment 1. Two participants were excluded from analysis of the ERP data due to a high level of noise in the data. Thus, data of 18 participants were included in the analysis. In total, 37.70 % of trials were excluded because of incorrect answers or noise. Time windows were identical to Experiment 1. For TF analysis, four participants were excluded, because they had no trials left for some of the conditions. Average reject rates were 39.39% (*SD* = 14.27%) of trials with individual rates ranging from 17.80% to 65.60% of trials.

Data analysis. Data analysis for the behavioral, ERP and TF data was identical to Experiment 1.

2.3.2 Results

2.3.2.1 Behavioral data. For accuracy, an effect of condition was found ($W(2) = 8.011$, $p = .018$, $R^2 = 0.005$). Post-hoc tests revealed that accuracies were higher for the O+P+ compared to the O-P- condition ($z = 2.654$, $p = .024$, $d = 0.462$) and marginally higher compared to the O-P+ condition ($z = 2.252$, $p = .073$, $d = 0.397$). No difference was found between the O-P+ and the O-P- condition ($z < 1$, $p = 1.000$). Reaction times revealed a main effect of condition ($W(2) = 147.330$, $p < .001$, $R^2 = .044$). Post-hoc pairwise comparisons revealed significant differences for the O+P+ condition compared to the O-P- condition ($t(1825) = -11.676$, $p < .001$, $d = .677$) and for the O-P+ condition compared to the O-P- condition ($t(1825) = -8.755$, $p < .001$, $d = .512$). The contrast between the O+P+ and the O-P+

condition also reached significance (z = -2.833, p = .014, d = 0.164). A descriptive summary of accuracies and reaction times of Experiment 2 can be seen in Table 9.

2.3.2.2 ERP results.

Confirmatory analysis. For the orthographic time window, a significant main effect of condition was found ($W(2)$ = 29.596, p < .001, R^2 = 0.003). While main effects of anterior-posterior distribution ($W(2)$ = 90.333, p < .001, R^2 = 0.009) and lateralization ($W(2)$ = 7.323, p = .026, R^2 = 0.001) reached significance, the interactions between condition and anterior-posterior distribution ($W(4)$ = 6.363, p = .174) and between condition and lateralization ($W(4)$ = 2.021, p =.732) were not significant. A planned t-test revealed a significant difference in mean amplitude between the O+P+ and the O-P+ condition ($t(9052)$ = 3.372, p = .002, d = 0.087). Here, the O-P+ condition showed a more negative-going wave than the O+P+ condition. The contrast between the O+P+ and O-P- condition was also significant ($t(9052)$ = 5.377, p <.001, d = 0.140). The O-P- condition showed a more negative-going wave compared to the O+P+ condition.

For the phonological time window, results again indicated a main effect of condition ($W(2)$ = 32.231, p < .001, R^2 = 0.003) as well as significant main effects of anterior-posterior distribution ($W(2)$ = 249.085, p <.001, R^2 = 0.024) and lateralization ($W(2)$ = 11.664, p =.003, R^2 = 0.001). The interaction term between condition and later alization was not significant ($W(2)$ < 1, p = .992), but the interaction between condition and anterior-posterior distribution yielded a significant result ($W(4)$ = 12.421, p = .015, R^2 = 0.029). The interaction arose, because the factor condition exhibited significant differences at central and parietal electrode sites ($W(2)$ = 37.622, p < .001, R^2 = 0.006), but not at frontal electrode sites ($W(2)$ = 3.230, p = .199). A planned t-test at central and parietal electrode sites showed a significant difference in mean amplitude between O-P+ and O-P- ($t(6029)$ = 4.644, p < .001, d = 0.148) and between the O+P+ and the O-P- condition ($t(6023)$ = 5.809, p <.001, d = 0.185). The unrelated condition showed a more negative-going wave than both phonological overlap conditions. Grand-average ERPs are shown in Figure 10.

Table 8

Mean values of language skills, age of acquisition and time spent in an English-speaking country of participants in Experiment 2 on the role of orthography in auditory priming

	Oral production	**Listening comprehension**	**Written production**	**Reading comprehension**	**Overall language skills**	**Age of Acquisition (in years)**	**Time spent in an English-speaking country (in months)**
RT experiment	3.100 (0.650)	3.220 (0.770)	2.940 (0.650)	3.340 (0.630)	3.140 (0.670)	9.960 (2.130)	3.040 (4.940)
EEG experiment	2.980 (0.680)	3.150 (0.670)	2.760 (0.660)	3.230 (0.700)	3.030 (0.570)	9.700 (2.770)	6.900 (11.370)

Note. Values and labels of rating scale: 1 = “beginner”, 2 = “intermediate”, 3 = “advanced”, 4 = “native-like”. Standard deviations in brackets.

Table 9

Descriptive summary of behavioral measures of Experiment 2 on the role of orthography in auditory priming

Condition	Accuracy		Reaction Times				
			raw RTs (in ms)			log RTs	
	n	*M*	*n*	*M*	*SD*	*M*	*SD*
O+P+	750	0.843	619	902.375	249.880	-134.669	245.174
O-P+	750	0.809	593	925.441	260.435	-109.997	246.437
O-P-	750	0.816	596	1,013.958	261.797	-14.574	231.314

Note. Accuracy equals the proportion of correctly answered trials of all critical real word trials in the respective condition. *n* = number of trials.

Table 10

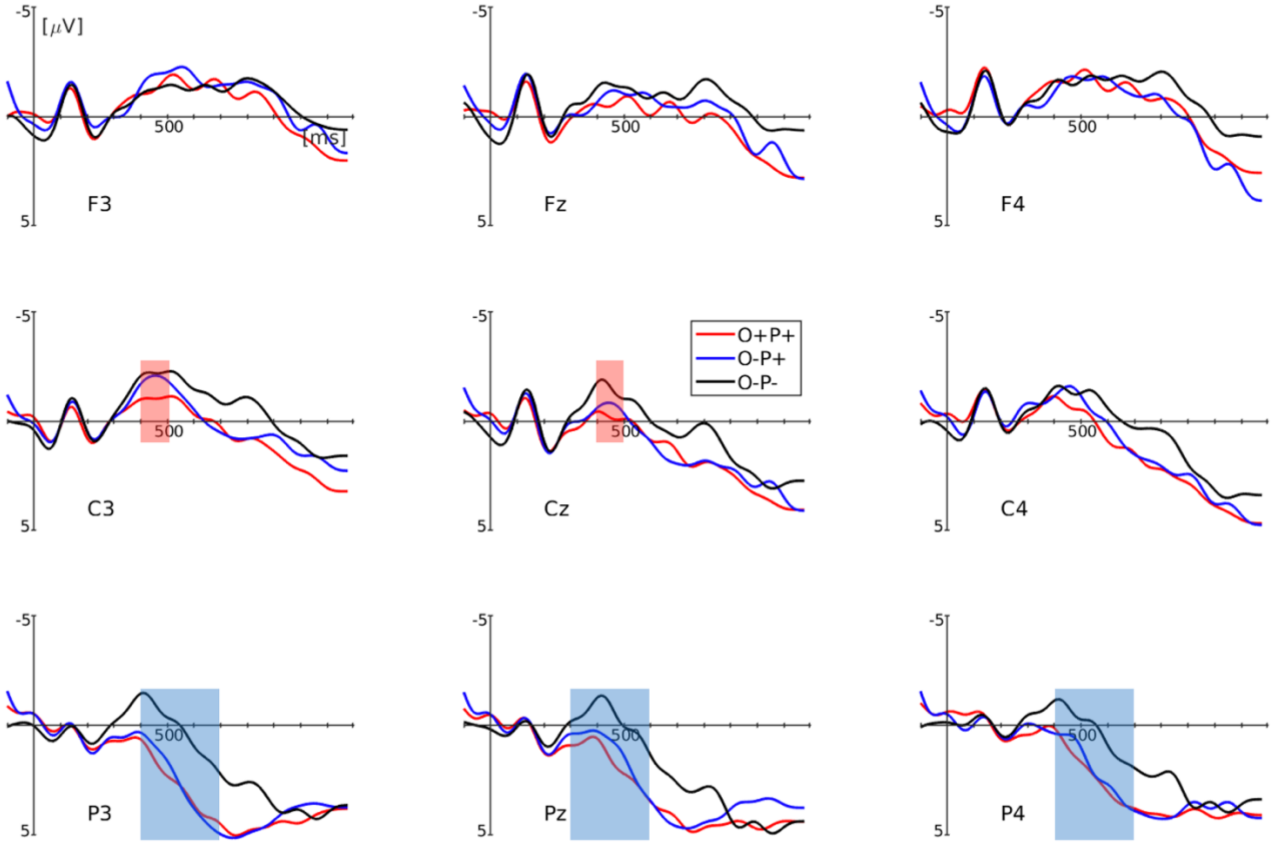
Results of post-hoc analyses in consecutive 50 ms epochs between 300 and 700 ms at three regions of interest for Experiment 2 on the role of orthography in auditory priming

	Orthographic priming effect			Phonological priming effect		
Epoch (ms)	frontal	central	parietal	frontal	central	parietal
300-350	-	-	-	-	-	-
350-400	< .10	< .10	< .10	-	-	-
400-450	-	-	-	<.01	< .01	< .01
450-500	< .001	< .001	< .001	-	-	-
500-550	-	-	-	-	-	< .001
550-600	< .05	-	-	-	-	< .001
600-650	-	-	-	< .001	< .001	< .001
650-700	-	-	-	-	< .05	< .001

Note. From “Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language” by S. Türk and U. Domahs, 2022, *Brain and Language, 235*, 105186, p. 8 (https://doi.org/10.1016/j.bandl.2022.105186). Copyright 2022 by Elsevier.

Figure 10

Grand-average ERPs over nine electrodes of Experiment 2 on the role of orthography in auditory priming



Note. Negativities are plotted upwards. The orthographic priming effect (O+P+ compared to O-P+ and O-P-, 400-500 ms) is marked with a red box, the phonological priming effect (O-P+ and O+P+ compared to O-P-, 400-700 ms) is marked with a blue box. An 8 Hz lowpass filter was applied to the ERP plot for better visualization.

Analysis of consecutive 50 ms epochs. Results of the analysis in successive 50 ms epochs are shown in Table 10. The linear mixed effects model showed significant main effects of all fixed factors ($W(2) > 55.238$, $p < .001$, $R^2 = 0.001\text{-}0.003$) as well as significant interactions between condition and epoch ($W(14) = 29.467$, $p = .009$, $R^2 = 0.006$) and between condition and anterior-posterior distribution ($W(4) = 48.038$, $p < .001$, $R^2 = 0.016$). The three-way interaction between condition, anterior-posterior distribution and epoch did not reach significance ($W(28) = 16.233$, $p = .965$). The effect of orthographic overlap was present in the epochs 350 to 400 ms and 450 to 500 ms with no specific localization. In the epoch 550 to 600 ms the effect was only localized at anterior electrode sites. The effect of phonological overlap was broadly distributed in an epoch of 400 to 450 ms. From 500 ms onwards, the effect was localized at parietal and central regions.

2.3.2.3 TF results.

The following table gives an overview of all TF effects found for Experiment 2 on the role of orthography in auditory priming. A comprehensive description of all statistical results can be found in Appendix B.

Table 11

Overview of TF results of Experiment 2 on the role of orthography in auditory priming

Orthographic time window			
Power			
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O+P+ > O-P-	delta	parietal	midline, right
O+P+ < O-P+, O-P-	theta	frontal	left, midline
		central	left
O+P+ < O-P+	theta	central	midline
		parietal	left, midline, right
O+P+ < O-P-	alpha	frontal	left, midline
		central	left
		parietal	midline
O+P+ > O-P+	alpha	central	right
O+P+ < O-P-	beta	frontal	right
		parietal	left
O+P+ < O-P+	beta	frontal	midline
O+P+ < O-P- O+P+ > O-P+	beta	central	left
O+P+ < O-P+, O-P-	beta	central	midline, right
		parietal	midline, right
O+P+ > O-P+, O-P-	gamma	frontal	left, midline
		central	left, midline
		parietal	left, midline, right
O+P+ > O-P+	gamma	frontal	right
		central	right
ITPC			
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O+P+ > O-P-	delta	frontal	left, midline
		central	midline
O+P+ > O-P-	theta	frontal	left, midline, right
		central	midline, right
O+P+ > O-P-	alpha	frontal	midline, right

O+P+ < O-P+	alpha	central	left
O+P+ < O-P-	alpha	parietal	midline
O+P+ < O-P+, O-P-	alpha	parietal	left
O+P+ < O-P+, O-P-	beta	frontal	left, midline, right
		central	left, midline, right
		parietal	left, right
O+P+ < O-P+, O-P-	gamma	frontal	left, midline
		central	right
		parietal	right
O+P+ < O-P+	gamma	frontal	right
		central	midline
		parietal	midline
Phonological time window			
Power			
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O-P- < O-P+	delta	frontal	left, midline, right
O-P- < O+P+	delta	parietal	left, midline, right
O-P- > O-P+	delta	central	left
O-P- > O+P+	theta	frontal	left, midline, right
O-P- > O-P+, O-P-	alpha	frontal	left, midline, right
		central	right
		parietal	left, midline, right
O-P- > O-P+	alpha	central	left
O-P- > O-P+, O+P+	beta	frontal	right
		central	left, midline, right
		parietal	left
O-P- > O-P+	gamma	frontal	right (O-)/left (O+)
O-P- < O+P+		central	midline
O-P- < O-P+, O+P+	gamma	central	left
		parietal	left/broadly
O-P- < O+P+	gamma	central	right
ITPC			
Effect	**Frequency band**	**Anterior-posterior distribution**	**Lateralization**
O-P- < O-P+, O+P+	delta	frontal	left, midline
O-P- < O-P+	delta	central	left
O-P- < O-P+, O+P+	theta	frontal	left, midline, right
		central	left, midline
O-P- > O+P+	theta	parietal	right

O-P- < O+P+	alpha	frontal	midline, right
		central	midline
O-P- < O-P+	alpha	central	left
O-P- > O-P+, O+P+	alpha	parietal	left, midline
O-P- > O-P+, O+P+	beta	frontal	left
O-P- > O+P+	beta	frontal	midline, right
		central	midline, right
O-P- < O-P+	beta	central	left
		parietal	left
O-P- > O+P+	gamma	frontal	midline, right
		central	midline, right
		parietal	midline, right
O-P- > O-P+, O+P+	gamma	parietal	left
O-P- < O-P+	gamma	central	left
		parietal	right

Note. O+P+ = orthographically and phonologically related, O-P+ = phonologically related, O-P- = unrelated.

2.3.3 Summary

Experiment 2 was conducted to test if late German-English bilinguals would show similar influences of orthography on spoken word recognition as the English native speakers tested by Perre et al. (2009) or the German native speakers tested in Experiment 1. Like in the previous experiment, behavioral data indicate an advantage for phonological overlap and for orthographic and phonological overlap in reaction times compared to the unrelated condition. Again, the orthographic overlap (O+P+) led to higher accuracies and faster reaction times in addition to the phonological priming (O-P+) effect, and this time, the difference was significant, indicating a phonological as well as an orthographic priming effect in the reaction time data.

For the ERP data, the phonological time window showed a reduced N400 for phonological overlap (O-P+, O+P+) compared to the unrelated condition (O-P-) in accordance with the findings reported by Perre et al. (2009) and in Experiment 1. Again, an interaction with anterior-posterior distribution showed a localization at central and parietal electrode sites. The time-course revealed effects from 400 ms onwards. Hence, the latency and distribution of the phonological priming effect is highly comparable with the results reported by Perre and colleagues and the findings of Experiment 1.

For the orthographic effect, Perre and colleagues found a reduced negativity for the O+P+ condition compared to the O-P+ condition for their native English speakers in English. Contrarily, the late German-English bilinguals tested with German stimuli in Experiment 1 showed a more negative-going wave for the O+P+ compared to O-P+ condition in the orthographic time window. Results of late German-English bilinguals tested in English of Experiment 2 are in line with the findings reported by Perre and colleagues (2009). A reduced N400 was found for orthographic and phonological overlap (O+P+) compared to only phonological overlap (O-P+), indicating facilitative processing of a target word preceded by an orthographically related prime. The time course showed significant influences of orthography on auditory target processing from 350 ms onward. The orthographic priming effect in this study seems to be more broadly distributed than previously reported, because no significant interaction between condition and anterior-posterior distribution was found in the orthographic time window. Nonetheless, the current findings replicated those found by Perre and colleagues revealing a facilitating orthographic priming effect during spoken word recognition for late German-English bilinguals in English.

TF measures generally showed reduced power for the O-P- condition compared to both conditions with phonological overlap in the delta and gamma bands, while in the theta, alpha and beta bands, power was higher for the O-P- compared to the O-P+ and the O+P+ conditions. Reduced ITPC was found for the O-P- compared to both primed conditions in the delta and theta band, while ITPC was increased in the beta and gamma bands. The alpha band showed heterogeneous patterns with regards to ITPC with both increases and decreases for the O-P- condition compared to the other two conditions. All in all, these results seem to be more inconsistent than those observed in Experiment 1. Delta band desynchronization for the O-P- condition indicates less cognitive engagement with the unprimed condition compared to the primed conditions. Similarly, higher power in the alpha band for the O-P- condition reveals less attention towards the unprimed condition and inhibition of processing less relevant stimuli. This is in line with the results of Experiment 1 and is indicative of phonological priming. However, because beta desynchronization is associated with expectation violations, power and ITPC in the beta band should be lower for the O-P- condition but have been found to be higher. Moreover, results in the theta and gamma band are ambiguous: Higher power, but decreased ITPC has been found in the theta band for the O-P- condition compared to the conditions with phonological overlap, when both should have been higher for the unprimed condition due to increased efforts in lexical access. For the gamma band, power was overall reduced for the O-P- condition but ITPC was higher. Both should have been increased for the unprimed condition relative to the primed conditions due to repetition suppression for primed conditions.

For the orthographic effect, TF analyses revealed power increases in the delta and gamma bands for the O+P+ compared to the O-P- (delta) and compared to the O-P- and the O-P+ conditions (gamma) as well as decreased power in the theta, alpha and beta bands for the O+P+

condition compared to the O-P+ and the O-P- conditions. Increased ITPC for the O+P+ condition compared to the O-P- condition was found in the delta and theta bands, while ITPC was lower for the O+P+ compared to the other two conditions in the alpha, beta, and gamma band. Delta desynchronization for the O-P- compared to the O+P+ condition again indicates less cognitive engagement with the unprimed condition. Higher alpha power and ITPC for the O-P+ and the O-P- conditions reveal less attention towards these conditions compared to the O+P+ condition. Decreased theta power for the O+P+ condition indicates facilitated lexical access for the condition with orthographic overlap compared to the other two conditions. However, ITPC in the theta band was increased for the O+P+ condition. Again, results showed inconsistencies. Beta power and ITPC were lower for the O+P+ condition compared to the other two conditions which is indicative of an expectation violation when both should have been higher for the more primed condition. In the gamma band, power and ITPC should have been reduced for the O+P+ condition compared to the more unprimed conditions, however lower gamma band activity was only found in ITPC, while power was higher.

All in all, the results of Experiment 2 replicate the findings of Perre and colleagues (2009) found for English native speakers and show facilitation of target processing for orthographic and phonological overlap compared to only phonological overlap in spoken word recognition in late German-English bilinguals. This indicates that the processing of orthographic information during spoken word recognition is modulated by the orthographic depth of the target language. Results of the TF analysis were more inconsistent in the second experiment compared to Experiment 1, which might be due to English being the second language. This might indicate more stable cognitive mechanisms underlying native language processing compared to processing of a late acquired second language. Nonetheless, notable differences can be observed in the theta, alpha and gamma frequency ranges. In Experiment 1, power and ITPC in the theta, alpha and gamma band were higher for the O+P+ compared to the O-P+ condition. However, in Experiment 2, theta power, alpha power and ITPC as well as ITPC in the gamma band were reduced for the O+P+ compared to the O-P+ condition. Thus, differences in orthographic processing between the two languages might indeed be modulated by inhibitory and facilitatory processes in these frequency ranges in German and English, respectively.

2.4 Discussion

The aims of this study were twofold: First, I wanted to investigate whether the influence of orthography on spoken word recognition found in native speakers of deep orthographies would also be present in native speakers of a shallow orthography. The experiment with

German native speakers in German revealed a clear phonological priming effect that was apparent in reduced reaction times and a reduced N400 amplitude for phonological overlap compared to the unrelated condition. An orthographic effect was limited to the neurophysiological data and showed a higher N400 amplitude for the orthographic and phonological overlap condition (O+P+) compared to words that overlap only phonologically (O-P+), while no difference was found compared to the unrelated condition. Thus, the orthographic overlap counteracts any facilitation of phonological overlap in a way that results in equal processing for the orthographic overlap condition and the neutral baseline (O-P-). TF measures revealed higher power and ITPC in the theta, alpha and gamma frequency bands for the O+P+ compared to the O-P+ condition, while these were reduced compared to the O-P- condition. Thus, the observed “anti-facilitation effect” for orthographic overlap might be due to inhibitory processes in these frequency bands.

The second experiment was conducted in English to investigate whether German-English late bilinguals would show comparable effects to the German native speakers of Experiment 1 or to the English native speakers tested by Perre et al. (2009), who showed a reduced N400 effect in the orthographic and phonological overlap condition compared to the condition with only phonological overlap. For the German-English bilinguals, a clear phonological priming effect was observable as reduced reaction times and a reduced N400 for phonological overlap compared to the unrelated condition. The data showed an orthographic priming effect in the reaction times and an even stronger reduction of the N400 amplitude for orthographic and phonological overlap than the phonological overlap condition. These results replicate the findings previously reported for native speakers of deep orthographies and point to a facilitating priming effect for orthographic overlap during spoken word processing in the L2 English. Here, theta power, alpha power and ITPC as well as ITPC in the gamma range were lower for the O+P+ compared to the O-P+ and the O-P- condition.

These results, therefore, demonstrate a clear influence of orthographic depth on the nature of the interaction between orthography and phonology in spoken word recognition: While orthographic overlap in spoken word processing produces clear facilitating effects in a deep orthography, the effects were inhibitory in nature in a shallow orthography. It was initially assumed that bimodal processing would be diminished or absent in German as a shallow orthography, because due to smaller grain sizes and less heterographic homophones, the additional activation of orthographic representations was considered to be unhelpful. Contrarily, the neurophysiological data showed a clear influence of orthography in German. However, the findings provide evidence that the additional activation of orthography in spoken word recognition in a shallow orthography comes with a cost. These findings are in agreement with previous results of reduced effects for shallow orthographies in bimodal research paradigms and in orthographic consistency paradigms (Frost & Katz, 1989; Pattamadilok, Morais et al., 2007; Ventura et al., 2004). Because the number of homophonic heterographs is comparably small in shallow orthographies, the activation of sub-lexical and lexical orthographic units in spoken word processing does not add any information to the activated articulatory features that serve to access a semantic entry in the mental lexicon. The results also clearly provide evidence for a flexible adaptation of cognitive and brain mechanism in bimodal processing to the orthographic depth of the target language in accordance with the second hypothesis. This is in line with previous results reporting a differential recruitment of different brain regions in bilingual visual word processing as a factor of the target language's orthographic depth (e.g., Buetler et al., 2014; Das et al., 2011; Jamal et al., 2012; Kumar, 2014; Nelson et al., 2009).

Moreover, the neurophysiological data not only point to a lack of an orthographic priming effect in shallow orthographies but indicate an inhibitory effect that becomes apparent as higher N400 amplitudes for orthographic and phonological overlap compared to mere phonological overlap in spoken word recognition. Had there been no effect of orthographic overlap at all in German, there should not have been a difference between the O+P+ and the O-P+ condition. The observed pattern of results speaks for an "anti-facilitating" effect that indicates lateral inhibition of orthographically related items at either the sub-lexical or lexical level of processing that counteracts the facilitation exhibited by phonological overlap between prime and target. This is supported by higher power and ITPC in the theta band for the O+P+ compared to the O-P+ condition in German, which might indicate inhibited lexical access for targets with orthographic overlap and, hence, lateral lexical inhibition of orthographically related words. Moreover, alpha and gamma synchronization for the O+P+ condition compared to the O-P+ condition might also indicate inhibition at sensory and conceptual levels. Alpha band synchronization has been specifically associated with anticipatory biasing by inhibiting one modality in favor of another (Foxe & Synder, 2011). Thus, inhibition of the orthographic modality might be advantageous in the processing of spoken German words. Notably, neighborhood size and neighborhood frequency effects on orthographic priming in visual word recognition have been found to be language specific as well. Effects have been found to be facilitative for English, but inhibitory for languages such as French, Dutch or Spanish (e.g., Carreiras et al., 1997; Grainger, 1990; Grainger & Segui, 1990; Sears et al., 1995; Siakaluk et al., 2002; van Heuven et al., 1998). These differences have been attributed to the orthographic depth of the target language and have given rise to the discussion that orthographic representations are organized differently for languages with a (more) transparent grapheme-to-phoneme-mapping compared to a language with an opaque orthography.

The cause for these observed differences between English and other, more transparent languages, is still under discussion. Possible reasons are seen in the representation of orthography and phonology in different grain sizes as pointed out in the introduction. The facilitating effects of orthographic neighbors in English might be observed due to the similarity in the rhymes between orthographic neighbors (Andrews, 1997). Moreover, lexical inhibition is argued to play a greater role in transparent orthographies than in an opaque orthography due to a higher amount of lexical competition of orthographic neighbors. A reason for this might be differences in the neighborhood structures between English and more transparent orthographies. English words tend to have more orthographic neighbors due to a higher number of monosyllabic words and, therefore, more high-frequency neighbors that necessitate weaker inhibitory connections, so low-frequency words have a chance to reach enough activation to be accessed (Sears et al., 2006).

The findings presented here are compatible with the Bimodal Interactive Activation Model (BIAM). I found inhibitory influences of orthography on spoken word recognition in German, spoken word processing in shallow orthographies is, therefore, bimodal. Moreover, activation-based models assume lateral inhibition between representational units on each level of processing (McClelland & Rumelhart, 1981). The number of excitatory and inhibitory connections between units depends on a variety of factors such as the extent of orthographic overlap, word frequency, and the orthographic neighborhood size (Andrews, 1989, 1992, 1997).

There is an ongoing debate whether effects of orthography on spoken word processing are lexical or pre-lexical (e.g., Pattamadilok, Kolinsky et al., 2007; Pattamadilok, Morais et al., 2007; Muneaux & Ziegler, 2004; Ventura et al., 2004; Ziegler, Muneaux & Grainger, 2003). Given the language specific differences observed in this study and the latency of the effects of around 400 ms, the observed effects could be attributed to processes at the lexical level. However, I manipulated the rhyme of the auditorily presented words, while ERPs were measured from target onset. Thus, I expect rhyme effects at the offset of words to evoke later ERP responses than onset effects, meaning that a negative deflection around 400 ms may reflect pre-lexical processing rather than lexical (Desroches et al. 2009). This is in accordance with previous results on phonological rhyme priming that have been allocated to pre-lexical processes (e.g., Norris et al., 2002; Slowiaczek et al., 2000). In my study, effects of orthographic rhyme priming had a similar latency than the effect of previously reported phonological rhyme priming and can, therefore, also be considered pre-lexical (see Perre et al., 2009 for a similar argument).

Other studies investigating orthographic influences on auditory word processing also suggest a pre-lexical involvement of orthography. Ziegler, Muneaux and Grainger (2003) used an auditory lexical decision task in French and presented words with large and small phonological neighborhoods (PN) and large and small orthographic neighborhoods (ON). While a large number of phonological neighbors led to higher reaction times and lower accuracies than words with few phonological neighbors, the effect of ON size was facilitating in nature. Had the ON effect been lexical, Ziegler and colleagues should have observed inhibitory priming. The fact that the ON effect was facilitating indicates sub-lexical processing. Taft et al. (2008) used a pseudohomograph priming paradigm in an auditory lexical decision task. They presented participants either with pseudoword primes that can be spelled like the target (e.g. /dri:d/ - /drɛd/, spelling of target: *dread*) or pseudoword primes that were equally phonologically related, but cannot be spelled like the target (e.g. /ʃri:d/ - /ʃrɛd/, spelling of target: *shred*). Participants were unaware of the relationship between primes and targets and could not have relied on strategic processes. Pseudohomographs facilitated target processing more than the phonologically related, but non-homographic primes. Again, this result suggests a sub-lexical involvement of orthography in spoken word processing.

Some limitations of this study need to be discussed. It could be argued that the differences in processing arose not because of the overall orthographic transparency of the language, but because of the differences in the stimulus material between the German and English study. First, English and German stimuli differed in Levenshtein distance. Consequently, the orthographic distance between O-P+ and O+P+ primes was higher in English than in German, which should lead to a higher orthographic priming effect in English. However, the effect in the German study points to an inhibitory effect of orthographic overlap that cannot be explained by the Levenshtein distance. Rather, I would expect the inhibitory effect to be even more pronounced if Levenshtein distance for the German stimuli was higher. Second, the stimuli of Experiments 1 and 2 differed with regard to the orthographic neighborhood size. The orthographic neighborhood size for the German stimuli was significantly smaller than for the English stimuli. However, again, I would expect lateral lexical inhibition to be higher the more orthographic neighbors a word has. Third, English and German stimuli differed in prime frequency, because O-P+ primes are rarer in German as a language with more transparent phoneme-grapheme-correspondences. Previous results on the orthographic consistency effect showed stronger effects of consistency for low-frequency words than for high-frequency words in a lexical decision task (Petrova et al., 2011).

However, in my priming studies, the target frequency did not differ between the two languages (*t*(141.294) = 1.380, *p* =.170), but prime frequency did and, thus, the discrepancy between prime and target frequency was higher in German than in English. Studies investigating orthographic priming in visual word recognition yield some indication that a low-frequency prime inhibits processing of a high-frequency target when prime and target are orthographic neighbors (e.g., Grainger, 1990; Massol et al., 2015; Nakayama et al., 2008; Segui & Grainger, 1990). The inhibitory effect becomes apparent as higher reaction times or a higher N400 amplitude for the orthographically related condition compared to an unrelated condition. However, this was not the case in this study: Inspection of the contrast between the O+P+ and the O-P- condition showed significantly reduced reaction times for the O+P+ compared to the O-P- condition and no statistical difference for the N400 amplitude in the orthographic time window. The inhibitory effect in my study was limited to the orthographic and phonological overlap condition compared to only phonological overlap and was only apparent in the neurophysiological data. However, as outlined above, the direction of the orthographic priming effect is influenced by an interaction between orthographic neighborhood size, relative prime-target-frequency and the orthographic depth of the writing system. Therefore, it cannot be ruled out that the characteristics of the German stimuli might have contributed to the effect. Furthermore, as I used the stimulus set of Perre and colleagues (2009) for the second experiment, the observed effects in the English experiment might be specific to the stimulus material. Further research is necessary to generalize the effects over other sets of stimuli.

Furthermore, it could be assumed that the differences observed between the O-P+ condition and the O-P- condition are not only driven by phonological, but also by orthographic similarities, because the O-P+ condition shared more graphemes with the target (e.g., *leaf – reef*) than the O-P- condition (e.g., *sick – reef*). Consequently, differences of the effects could be attributed to orthographic rather than purely phonological factors. However, Perre and colleagues (2009) as well as the current experiments have shown that the topographic and temporal distribution of the orthographic and phonological effects can be differentiated from each other by means of the neurophysiological measures that were used. The fact that the effects can be differentiated speaks for different underlying mechanisms that drive the effects of orthographic overlap (O+P+ compared to O-P+) and phonological overlap (O-P+ and O+P+ compared to the O-P- condition).

The orthographic priming effect in the German experiment was limited to the EEG data. Behavioral data did not reveal significant differences between the O+P+ and the O-P+ conditions in this experiment. In the English experiment, an orthographic priming effect could also be observed in the behavioral data as reduced reaction times for the O+P+ compared to the O-P+ condition. Descriptive statistics indicate that the orthographic overlap in addition to the phonological overlap produced higher accuracies and lower reaction times in both experiments, however, these differences were not significant in Experiment 1. This might be due to a lack of power for the behavioral data. Brysbaert and Stevens (2018) performed power calculations for reaction time analyses using linear mixed effects models and suggest at least 1,600 observations (40 participants and 40 stimuli) per condition for adequate power. The reaction time data in my experiments had 24 and 25 participants with 30 trials per condition, resulting in 720 and 750 observations per condition, respectively. This is less than half the observations recommended by the authors. Thus, a failure to find a significant orthographic priming effect in the behavioral data in the German experiment might have been due to power issues. Moreover, results from underpowered studies can be unreliable. A power calculation based on the method suggested by Kumle et al. (2021) using a smallest effect size of interest of 75% of the empirical beta coefficients revealed a power of nearly 100% for all effects in the German experiment. However, for the English experiment, power was only at 54.50% for the orthographic effect. Based on these values, power in the German reaction time study was adequate, while for the English study, power was diminished for the orthographic priming effect. A sample size of between 50 and 60 participants is necessary based on these calculations to reach a power of above 80% for the orthographic priming effect.

Further limitations arise in connection with the TF data. TF analyses revealed some inconsistent and at times contradicting results. This might be due to a number of reasons. Firstly, due to a lack of previous studies, the TF analyses were exploratory in nature. Despite an effort to reduce the number of statistical tests by only analyzing time windows and ROIs of the confirmatory ERP analysis, the number of statistical tests was quite high, because all frequency bands were analyzed. This inflates the Type I error and can lead to spurious significant results. Thus, it cannot be excluded that some of the findings, especially those limited to a single electrode, might reflect chance rather than true effects. Secondly, the number of trials for the TF analysis in both experiments was quite low. This was due to a high number of noise in the data that can be attributed to the choice of baseline. The baseline was chosen to be in the intertrial interval where participants tend to blink, hence, a high number of trials had to be excluded. This specifically affects the calculation of ITPC as it measures phase synchrony between trials (Morales & Bowers, 2022). If the number of trials is low, ITPC values might be overly biased by some untypical trials. Thirdly, inconsistencies were found to be more pronounced for the second experiment compared to the first. This was attributed to English being the second language of the participants in Experiment 2. The cognitive mechanisms underlying language processing in the non-native language might be less stable and homogeneous across participants. Even though participants generally had a high level of English as a second language, variance in L2 proficiency might have played a role in the higher inconsistency of the TF results in the second experiment.

In conclusion, the findings of this study clearly indicate that orthography influences spoken word processing in shallow and in deep orthographies, but the direction of effects is modulated by the orthographic depth of the target language. While orthographic overlap facilitates spoken word processing in English, the effect was of inhibitory quality in German. These findings are in line with previous results and are compatible with the BIAM. However, some issues have been raised in the discussion of this study. Firstly, it remains unclear whether the influence of orthography on spoken word processing had a lexical or pre-lexical locus. Secondly, differences in the stimulus material between the two languages rather than their orthographic depth could have contributed to the observed processing differences. Thirdly, the results of the TF measures were partly ambiguous. In the following study, I aimed to resolve these issues and replicate the findings.

3. Cross-modal transposed letter priming

3.1 Introduction

Though the auditory priming paradigm (Chéreau et al., 2007; Perre et al., 2009) that was used in the first series of experiments clearly showed differences in the influence of orthography on spoken word recognition as a factor of orthographic depth, this paradigm is not without limitations. One of the bigger problems this paradigm faces is the limited number of O-P+ primes available in shallow orthographies such as German. Due to lower feedback than feedforward consistency it is possible to find German words whose rimes are pronounced the same way but spelled differently (e.g., *Neid* ‘envy’, pronounced [naɪ̯t] vs. *Maid* ‘maiden’, pronounced [maɪ̯t]). However, because inconsistencies are rarer and less severe in German, which is innate to a shallow orthography, differences in the stimulus material between the two languages are hard to avoid. Thus, in the preceding series of experiments, German and English O-P+ stimuli differed in frequency, number of orthographic and phonological neighbors as well as Levenshtein distances between the two languages. This makes this paradigm unsuited for cross-linguistic comparisons as it is hardly possible to control for these factors across languages with different orthographic depths. In languages with an even more (feedback) consistent orthography than German this problem will only get more severe.[7]

Consequently, I turned to a paradigm that allows for better control of the cross-linguistic stimuli: transposed letter (TL) priming. This paradigm has heretofore been used in visual word processing. TL primes are constructed by transposing the position of two letters within a word (e.g., *jugde* – *judge*) and have been found to prime their base words better than orthographic controls (e.g., *jupte* - *judge*) (e.g., Grainger et al., 2006; Lupker et al., 2008; Perea & Carreiras, 2006; Perea & Lupker, 2004). Perea and Lupker (2003) used a masked priming paradigm with TL primes (e.g., *uhser* – *USHER*), identity primes (e.g., *usher* – *USHER*) and control primes constructed by replacing the transposed letters with unrelated letters (e.g., *ufner* – *USHER*). They found significantly reduced reaction times for the TL condition compared to the control condition as well as significantly reduced reaction times for the identity condition compared to the control condition. The TL priming effect was greatly reduced if the last letter of the word was transposed (e.g., *ushre* – *USHER*). This replicates findings by Chambers (1979) who found interference effects in a lexical decision task for TL non-words with word internal transpositions (*liimt* from ‘limit’) compared to TL non-words in which the first (*omtor* from ‘motor’) or last letters (*visti* from ‘visit’) were transposed. Consequently, TL non-words are more likely to be confused with a real word if the transposition occurs within the word. Their effects are taken as evidence for the coding of letter positions in a flexible way during visual word processing in skilled readers. This challenges models of visual word recognition that rely on the exact coding of letter positions within a word. If the exact position of a word-internal letter would be a pre-requisite for word identification, the letter string *jugde* should not be more similar to the target word *judge* than the letter string *jupte*. TL primes are taken as core evidence that this is not the case, and that word identification is possible even if the right letter order is not observed.

TL priming is tightly connected to the reading proficiency in a certain script and priming effects become more pronounced with increasing reading skills, be it in children in their L1 (e.g., Acha & Perea, 2008; Eddy et al., 2016; Ziegler et al., 2014) or in adults in their L2 (e.g., Meade et al., 2022; Perea et al., 2011). Ziegler et al. (2014) investigated the development of pseudo-homophone (PsH) and TL priming effects in French children of grades 1 to 5 using a

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[7] Please note that the studies presented in the following have been submitted or prepared for publication and the following chapter is taken in part from Türk and Domahs (in revision) and Türk and Domahs (in preparation) and has been adapted for this thesis.

sandwich masking paradigm. They presented the target word for 27 ms before presenting either a PsH (e.g., *blenc – BLANC*) or TL prime (e.g., *bouhce – BOUCHE*) for 70 ms that was replaced by the target. They found stable PsH priming effects in all grades indicating phonological involvement in reading throughout development. They also report a TL priming effect that was present in all grades but showed a tendency to increase in higher grades. More importantly, using reading age rather than grade as an indication of reading ability, the authors report a significant positive correlation between reading ability and the effect size of the TL priming effect. Similar results are reported by Eddy and colleagues (2016) using neurophysiological measures in children aged 8-10 years. They found that the magnitude of TL priming effects (e.g., *barin – BRAIN* vs. *bosin – BRAIN*) evident in the N250 and N400 components were significantly correlated with reading ability. Contrarily, PsH priming effects (e.g., *brane – BRAIN* vs. *brant – BRAIN*) did not correlate with reading ability.

Perea et al. (2011) used a same-different matching task with masked priming in Arabic with Arabic native-speakers, speakers of Arabic with a lower-intermediate level as well as individuals unfamiliar with the Arabic script. They report significant TL priming effects only for those participants who had experience with the Arabic script. Moreover, the TL priming effect was stronger in the L1 speakers compared to the L2 speakers. Similar results have been found by Meade et al. (2022) who report significant TL priming effects in the L1 English as well as the L2 Spanish in late English-Spanish bilinguals evident in the N250 and the N400 components. As the only language difference, they report a significant N400 modulation with higher N400 amplitudes in the dominant language English compared to the non-dominant language Spanish.

These results are evidence that with increasing familiarity in a language, readers rely less on the exact positioning of letters in a word and instead use a “good enough” approach with flexible letter-position coding (Meade et al., 2022). Grainger and Ziegler (2011) propose a dual-route processing strategy for skilled readers that differs in the use of orthographic information: One route involves coarse-grained orthographic representations to rapidly map orthographic code onto semantic meaning, called the “fast track to semantics” (Grainger & Ziegler, 2011, p. 3): Coarse-grained orthographic information is directly connected to whole-word orthography and to semantic meaning. The fast identification of word identity is achieved by coding the most detectable and informative letter combinations regardless of their positions within the word (Grainger et al., 2012; Grainger & Ziegler, 2011). The second slower route uses fine-grained orthographic code information, in which the precise order of letter positions is retained. Fine-grained orthographic information is connected to whole-word orthography and to sub-lexical phonological representations.

Contrarily, beginning readers rely on phonological recoding to decode orthographic information letter by letter and link it to whole-word phonological representations and from there to semantic meaning, thereby making use of exact letter positions in a word. With increasing script exposure and reading abilities, readers develop an orthographic lexicon that builds on coarse-grained and position-invariant coding schemes to rapidly and directly map orthographic information onto meaning without the need for phonological recoding strategies (Acha & Perea, 2008; Grainger & Ziegler, 2011; Ziegler et al., 2014). These coarse-grained representations are primarily based on letters and letter combinations that are most informative to a word's identity as often a subset of letters combined with their relative positioning and other information such as word length is sufficient to decode an orthographic word and access its semantic meaning in the lexicon (Meade et al., 2022). Likely, the informativity of letters with regard to a word's identity and thus the coarse-grained orthographic representations have to be learned in L1 as well as L2 reading acquisition, explaining why TL priming effects only occur after exposition to the respective script and increase with script exposure.

The proposal of Grainger and Ziegler (2011) of a dual-route processing of orthographic information can be implemented in the BIAM. They propose that orthographic processing is based on two types of orthographic information: coarse-grained and fine-grained. The coarse-grained route relying on a position-invariant orthographic lexicon leads to activation of whole-word orthographic units and from there to semantic meaning without activating sub-lexical phonological units. TL priming effects are taken as key evidence for this route: The exact letter position coding is not necessary for the activation of whole-word orthographic representations and their semantic meaning as long as the specific characteristics of the orthographic word form are retained (most informative letters, word length, first and last letter in correct positions, etc.).

The fine-grained processing of orthographic code preserving the precise letter order involves both sub-lexical orthographic and phonological units that activate their corresponding whole-word units (Grainger & Ziegler, 2011). Pseudo-homophone priming is assumed to rely on this route as exact letter position coding is necessary to activate the corresponding phonemes in the right order to access whole-word phonological representations and semantic units. As Grainger and Ziegler (2011) argue, the introduction of a letter transposition in pseudo-homophones should eradicate the priming effect, because pseudo-homophone priming relies on exact letter position coding. This assumption is supported by studies presenting TL primes and TL pseudo-homophone primes (e.g., *relovución* /relobuˈθjon/ – *REVOLUCIÓN*, *relobución*

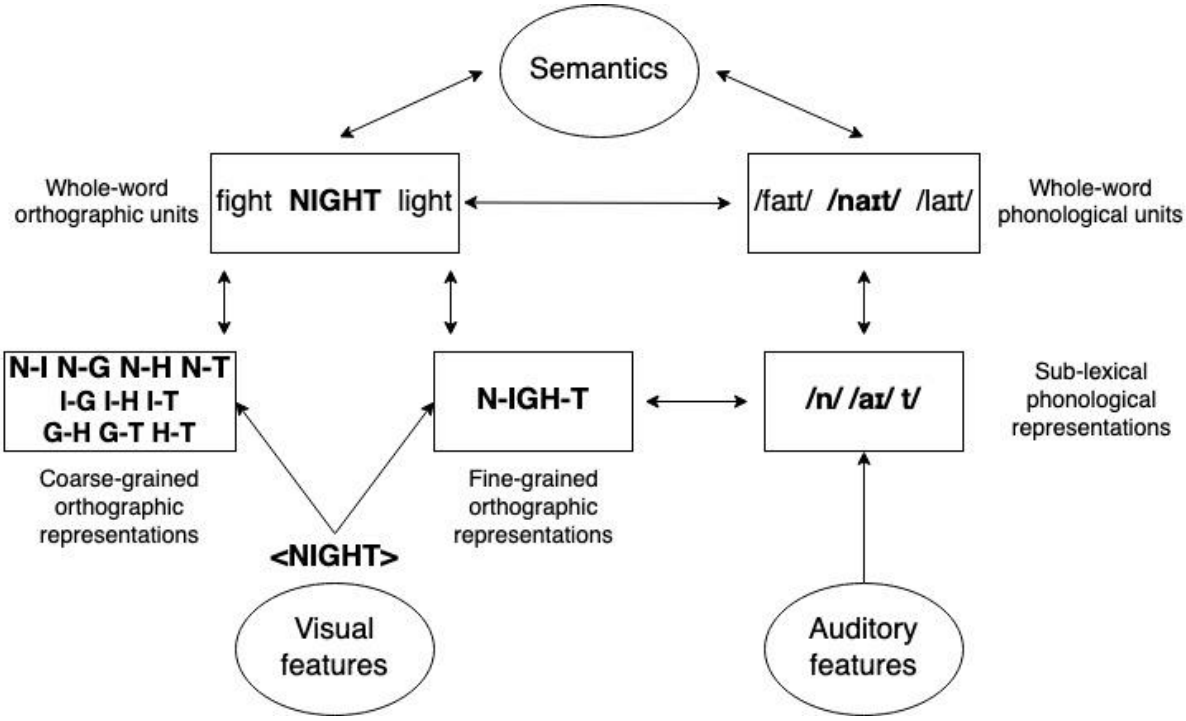
/relobuˈθjon/ – *REVOLUCIÓN*; Perea & Carreiras, 2006) and finding that TL pseudo-homophones do not significantly prime their target compared to a control condition. A visual depiction of the BIAM with the implemented coarse-grained and fine-grained routes is shown in Figure 11.

Following a study by Perea and Carreiras (2006) using pseudo-homophones of TL primes, TL priming effects have been attributed to sub-lexical orthographic, not phonological processing (e.g., Eddy et al., 2016; Grainger et al., 2006; Kinoshita & Norris, 2009; Meade et al., 2020; Perea & Carreiras, 2006, 2008). The authors used TL primes (e.g., *relovución* – *REVOLUCIÓN*), pseudo-homophones of the TL primes (e.g., *relobución* – *REVOLUCIÓN* – note that the letters <v> and <b> are pronounced identically in Spanish), and orthographic controls (e.g., *relodución* – *REVOLUCIÓN*). Using a masked priming paradigm, the authors found significant priming effects for TL primes compared to the TL pseudo-homophones. A comparison between the TL pseudo-homophone and the orthographic control revealed no differences, indicating that TL pseudo-homophones, though the phonology is identical to the TL primes, do not facilitate processing of their base word (Perea & Carreiras, 2006, Experiment 1). Hence, they argue that "TL similarity effects are orthographic – rather than phonological – in nature" (Perea & Carreiras, 2006, p. 1600).

Meade and colleagues (2020) investigated TL priming effects in deaf participants as a means to explore whether phonological information is necessary to form orthographic representations. They compared a group of hearing and deaf participants and used adjacent and non-adjacent TL primes (adjacent: e.g., *chikcen* – *CHICKEN*; non-adjacent: e.g., *ckichen* – *CHICKEN*) and orthographic controls (adjacent: e.g., *chidven* – *CHICKEN*; non-adjacent: e.g., *cticfen* – *CHICKEN*) with behavioral and neurophysiological measures and a sandwich masking paradigm. They found lower reaction times, higher accuracies and lower N250 and N400 amplitudes for words preceded by TL primes compared to words preceded by orthographic controls in both hearing and deaf readers. For both groups, TL primes were stronger for adjacent TL priming compared to non-adjacent TL priming, but priming effects were present for both types of primes. Importantly, the authors did not find an interaction effect between group and prime condition, neither in the reaction times and accuracies nor in N250 and N400 amplitudes. The effect of TL primes on target word processing was similar for hearing and deaf individuals indicating that phonological representations do not contribute to TL priming effects.

Figure 11

Depiction of the BIAM with the coarse-grained and fine-grained route



Note. From "Unimodal and cross-modal transposed letter priming effects in late German-English bilinguals are evidence for the bimodal processing of words", by S. Türk and U. Domahs, in revision, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, p. 10.

However, based on the findings of study 1 and the extensive literature reviewed in the General Introduction, I have established that word processing is bimodal in nature involving both orthographic and phonological information irrespective of the input modality. This is implemented as a core assumption in the BIAM via bidirectional links between orthography and phonology on sub-lexical and lexical levels. This still holds in part for the extension of the BIAM depicted in Figure 11. Even though, the coarse-grained route proposed for the processing of TL primes does not involve sub-lexical phonology, phonology is still involved in TL processing via links from whole-word orthography to whole-word phonology. This route might be slower, therefore accounting for the fact that in visual word recognition, the involvement of phonology will not be necessary as word identification will be achieved before the activation of phonology based on coarse-grained and whole-word orthographic representations. This also explains why in deaf participants, a TL priming effect is still observable. However, this does not mean that phonology is not involved at all in the processing of TL primes (in hearing participants), it might only be involved at a later stage of processing. This can be investigated by using a time-sensitive method such as EEG.

Consequently, I propose that TL priming effects should be observable across modalities if the assumptions of the BIAM hold. If spoken word processing is bimodal in nature, it should be possible to use an orthographic TL prime to pre-activate an auditory target, thus influencing its processing. Based on the previous results, the effect of visual TL primes on auditory target words might be dependent on the orthographic depth of the target language. Specifically, bimodal processing should be more helpful for English as a deep language than for German as a shallow language based on the assumptions and results of my previous study. Previously, I argued that bimodal processing is advantageous for deep languages because of a higher number of heterographic homophones. Activating orthography and phonology simultaneously therefore provides relevant additional information to solve ambiguous auditory input. This should not be the case for shallow orthographies, because the majority of homophones are also homographs, consequently the simultaneous activation of orthography and phonology is not helpful. The results of my previous study confirmed these assumptions: Orthographic overlap in spoken word recognition was facilitating in English but inhibitory in German. Moreover, the Psycholinguistic Grain Size Theory (PGST; Ziegler & Goswami, 2005) suggests that the size of orthographic units linked to phonological units is higher for deep than for shallow orthographies. While in shallow orthographies, grapheme-phoneme correspondences rely on smaller units, in deep orthographies these representations might only be connected at the rime or whole-word level. Because based on Figure 11, I assume that phonology is only involved at the whole-word level via whole-word orthographic representations, I hypothesize that bimodal activation of orthography and phonology will be stronger for English than for German, because the latter will have established links between orthography and phonology at a sub-lexical level, which according to Grainger and Ziegler (2011) is only possible via the fine-grained route. However, this route should not be activated by TL primes.

To my knowledge, cross-modal TL priming has never been investigated before. Cross-modal priming studies (visual prime - auditory target) have only been conducted with other kinds of primes and have shown that effects depend largely on prime visibility, which is influenced by the duration of the prime and the backward mask, with random consonant strings being described as the more efficient masking type (Grainger et al., 2003). Grainger and colleagues (2003) used a masked priming paradigm and presented participants with PsH (e.g., *nort*—*NORD*) and repetition primes (e.g., *nord – NORD*). They found repetition priming effects even at short prime durations (53 ms) but failed to find a PsH priming effect for durations shorter than 67 ms. Moreover, both the repetition and PsH priming effects did not interact with modality and, thus, had the same size within (visual prime – visual target) and across (visual prime – auditory target) modalities.

I conducted three experiments on unimodal and cross-modal masked priming using TL, repetition and PsH primes in native speakers of German in their L1 and their L2 English. In Experiment 1, I sought to replicate existing findings on L1 and L2 transposed-letter priming in the visual modality (visual prime - visual target) and ensure suitability of the stimulus material to evoke TL priming effects in both languages. I used a masked priming paradigm with a prime duration of 66.67 ms and presented participants with TL and repetition primes as well as an orthographic control condition. In Experiment 2, I used the same paradigm as in Experiment 1 with the exception that I presented for the first time TL primes in a cross-modal paradigm with a visual prime and an auditory target. Again, I tested speakers of German in their L1 and their L2. Moreover, I varied the prime visibility and presented the prime both with a duration of 66.67 ms and 50.00 ms. In the third Experiment, I used the cross-modal paradigm of Experiment 2 but presented TL primes and PsH primes at prime durations of 50 ms to differentiate between orthographic and phonological contributions to cross-modal priming effects. While Experiment 1 only reports behavioral evidence, in Experiments 2 and 3, I combine neurophysiological and behavioral methods. The neurophysiological investigation serves to get information on the time-course of activation of orthographic information in the bimodal processing of TL primes in English and German and the underlying cognitive processes.

3.2 Experiment 1

In Experiment 1, I used a unimodal visual TL priming paradigm to test German native speakers in their L1 German and their L2 English. The goal of the experiment was to replicate previous findings with my stimulus material to ensure that the material and the experimental design are suitable to evoke TL priming effects in late German-English bilinguals. Thus, if I should fail to find a TL priming effect in the cross-modal designs of Experiments 2 and 3, this cannot be attributed to the stimulus material or the experimental design. Based on previous studies, I hypothesize that there should be significant TL priming effects for both the L1 and the L2 and that effects should be higher for the dominant L1 German compared to the L2 English.

3.2.1 Method

Participants. Forty-four participants (22 female; mean age: 26.24 years) were recruited via the mailing list of the University of Marburg, Germany, and assigned to one of the two languages (English, German). All participants were German native speakers and reported neither cognitive nor language impairment. For the English group, English LexTale (Lemhöfer & Broersma, 2012) test scores were collected. The LexTale is a short test for advanced learners of English to measure language skills based on a lexical decision task. The test has been specifically designed for cognitive experiments. The LexTALE test was administered to the participants after the main experiment. The mean LexTale score was 79.62% with a range between 58.75% and 95% and a standard deviation of 11.61%. The LexTale test is not normed for German native speakers, but taking the data normed with Dutch native speakers, this score corresponds to an upper intermediate to advanced level of English according to the authors.

Material. The goal for stimulus construction was to make the sets of stimuli as closely matched across English and German as possible to allow for cross-linguistic comparisons while controlling for influencing factors. Consequently, I took cognate words as the critical stimulus material. Cognate words are words that are closely related in pronunciation, spelling, and meaning across two languages (e.g., Engl. *film* – Ger. *Film*). However, due to their close similarities, cognate words are often processed differently than non-cognates because they are represented in both languages. To be able to clearly attribute observed effects to only one language, I selected 150 non-identical German-English cognates (e.g., Engl. *blouse* – Ger. *Bluse*). Non-identical cognate words differed in at least one grapheme/phoneme from each other to achieve a high similarity across languages whilst making sure that stimuli could be clearly attributed to one of the two languages. Moreover, I created a set of 150 German-English non-cognate translation equivalents (e.g., Engl. *bottle* – Ger. *Flasche*) to intermix them with the non-identical cognates to conceal the cognate status of the critical words and to ensure activation of only the target language. Previous studies have shown that non-identical cognates are processed differently than identical cognates and that the presence of non-identical cognates among identical cognates attenuates or cancels out the cognate facilitation effect. This effect is even more diminished in the presence of non-cognate translation equivalents (Arana et al., 2022; Comesaña et al., 2014; Dijkstra et al., 2010). Moreover, it has been shown that processing of the same stimulus is modulated by the language context (Buetler et al., 2014). Thus, the use of non-identical cognates and non-cognates in the same list ensures processing of a word in only the target language while keeping important characteristics such as phonology, orthography, and semantics as similar as possible between the two languages under investigation. Additionally, 150 pseudowords (e.g., Engl. *sicture,* Ger. *Frinke*) were constructed for each language by taking German and English existing words and exchanging word onsets. German and English native speakers reviewed the word lists to ensure that all pseudowords were in fact non-existent.

All items were between 5 and 8 letters and between one and two and a half syllables (half syllables are schwa syllables) long. German-English non-identical cognate pairs differed in length at most by one letter and/or a schwa syllable. As in the first study, the CLEARPOND database (Marian et al., 2012) was used to calculate frequency measures and orthographic and phonological neighborhood sizes for German and English. Non-identical cognates had a mean frequency of 44.2 per million for German and 48.7 per million for English. Non-cognates had a mean frequency of 25.2 per million for German and 19.8 per million for English. Stimuli were matched across languages with respect to frequency ($t(558) < 1$, $p = .844$) as well as orthographic ($t(558) < 1$, $p = .633$) and phonological neighborhood sizes ($t(558) = 1.581$, $p = .115$). This was also true when looking at non-identical cognates (frequency: $t(293) < 1$, $p = .664$; orthographic neighbors: $t(293) < 1$, $p = .554$; phonological neighbors: $t(293) = 1.303$, $p = .194$) and non-cognates (frequency: $t(263) = 1.237$, $p = .217$; orthographic neighbors: $t(263) < 1$, $p = .920$; phonological neighbors: $t(263) < 1$, $p = .330$) separately.

TL primes were constructed in three different ways to expand the pool of cross-linguistic stimuli: i) transpositions of adjacent consonant letters (e.g., Ger. *gatren– GARTEN*, Engl. *gadren – GARDEN*), ii) transposition of non-adjacent consonant letters (e.g., Ger. *perkeft– PERFEKT*, Engl. *perceft – PERFECT*) and iii) transposition of adjacent consonant-vowel letters (e.g., Ger. *paiper – PAPIER*, Engl. *paepr – PAPER*). The types of transposition were balanced across the stimulus material and were kept identical for non-identical cognate pairs. All these manipulations have previously been found to reliably evoke TL priming effects (e.g., Perea & Carreiras, 2006; Grainger et al., 2006; Perea & Lupker, 2004; Perea et al., 2008; Ziegler et al., 2014). However, no TL priming effects were found for the transposition of two vowels, hence this manipulation was not included in the stimulus material (Lupker et al., 2008; Perea & Lupker, 2004). Note that manipulations were limited to letters within the word (Perea & Lupker, 2003). An orthographic control condition was constructed by replacing the transposed letters with unrelated letters (e.g., Ger. *gapfen – GARTEN*, Engl. *gabpen – GARDEN*). The final condition consisted of a repetition priming condition (e.g., Ger. *garten – GARTEN*, Engl. *garden – GARDEN*) that served as an additional control to investigate how exchanging two letters within a word affects priming efficiency. The full stimulus material can be found in Table A2 of Appendix A.

Three stimulus lists were constructed for both languages. Each target appeared once per list with a different kind of prime. TL manipulations were balanced across the lists. This resulted in 150 non-identical cognates, 150 non-cognate translation equivalents and 150 pseudowords per list and 50 stimuli per condition per participant. Each participant was randomly assigned to a word list.

Procedure. The experiments were programmed using PsychoPy (Peirce et al., 2019) and were run online via Pavlovia (https://pavlovia.org/). First, a fixation cross was shown for 1,000 ms, then a forward mask consisting of hashmarks (#####) was presented for 500 ms before presenting the prime in lowercase letters for 66.67 ms. The number of hashmarks was identical to the number of letters of the prime. Afterwards, the target was presented in uppercase letters, and participants had to decide whether the target was an existing German or English word or a pseudoword. No timeout was set for the decision and no feedback was given during the experiment. Participants were instructed to answer as fast and as accurately as possible. The trial scheme is visualized in Figure 12.

Data analysis. Data were analyzed using R Studio and the lme4 package (Bates et al., 2015). Post-hoc tests were computed using the emmeans package (Lenth et al., 2021). Effect sizes for fixed effects were calculated using the MuMIn package (Bartón, 2020). Pseudowords and non-cognates were excluded prior to the analysis, thus, only the non-identical cognates were further analyzed, because they were closely matched across languages in the relevant stimulus characteristics. Accuracy was measured as a binary variable (1 = correct, 0 = incorrect) and analyzed with a logistic mixed effects model with condition (TL, repetition, control) and language (German, English) as fixed effects and by-subject and by-item random intercepts on single-trial data. Limited-memory BFGS implemented in the optimx package (Nash et al., 2022) was used as an optimizer to handle convergence issues.

Before the analysis of reaction time data, incorrect responses were excluded. This concerned 2.19% of all data points. Reaction times showed a significant right skew and were log-transformed prior to further analysis. Because the experiments were conducted online, there were a few obvious outliers present in the data that were clearly unrelated to the cognitive processes under investigation. I, therefore, excluded all reaction times lower than 350 ms and higher than 3,500 ms from further analysis. This concerned less than one percent of all datapoints. Cook's Distance was used to evaluate the presence of influential data points. None of the data points showed a value higher than $D_i = 0.325$, therefore, all lay below a suggested cut-off-threshold of $D_i < 1.000$. However, some values showed a higher Cook's Distance than a cut-off threshold of $D_i < 4/n$, where n denotes the sample size (Cook & Weisberg, 1982).

Visual inspection also confirmed some deviating data points. Consequently, these data points were excluded prior to further analysis. This concerned 1.13% of data points. Reaction times were analyzed using a linear mixed effects model (LMM) with condition (TL, repetition, control) and language (German, English) as fixed effects and by-subject and by-item random intercepts on single-trial data.

Type II Wald-Chi-Square tests were used to test the significance of fixed effects. Planned contrasts were used as post-hoc tests with the control condition as the reference condition. Contrasts were tested against the normal distribution with asymptotic degrees of freedom. Bonferroni correction was applied to account for family-wise error rates. The corresponding test statistic, *p* value and effect size for significant effects are reported.

3.2.2 Results

Overall, accuracies were higher for the L1 German than the L2 English and higher for the repetition condition compared to the TL and control condition (see Table 12). The logistic mixed effects model showed a main effect of condition ($W(2) = 14.037$, $p < .001$, $R^{2 =}$ 0.024), the main effect of language ($W(1) < 1$, $p = .543$) and the interaction between condition and language ($W(2) = 3.617$, $p = .164$) did not reach significance. Post-hoc tests revealed a significant repetition priming effect ($z = 3.742$, $p < .001$, $d = 0.938$), but no effect of TL priming ($z = 1.537$, $p = .248$). Reaction times were generally lower for the L1 German compared to the L1 English and lower for the repetition and the TL conditions compared to the control condition. The linear mixed effects model for reaction times showed a main effect of condition ($W(2) = 168.018$, $p < .001$, $R^2 = 0.017$). The main effect of language ($W(1) < 1$, $p = .620$) and the interaction between condition and language ($W(2) = 3.395$, $p = .183$) were not significant. Planned contrasts showed a significant repetition priming effect ($z = 12.638$, $p < .001$, $d = 0.390$) and a significant TL priming effect ($z = 4.055$, $p < .001$, $d = 0.125$). Descriptive statistics for accuracies and reaction times of Experiment 1 can be seen in Table 12. Table 13 shows net priming effects for repetition and TL priming of Experiment 1 per language and condition.

Figure 12

Trial scheme of Experiment 1 on unimodal TL priming

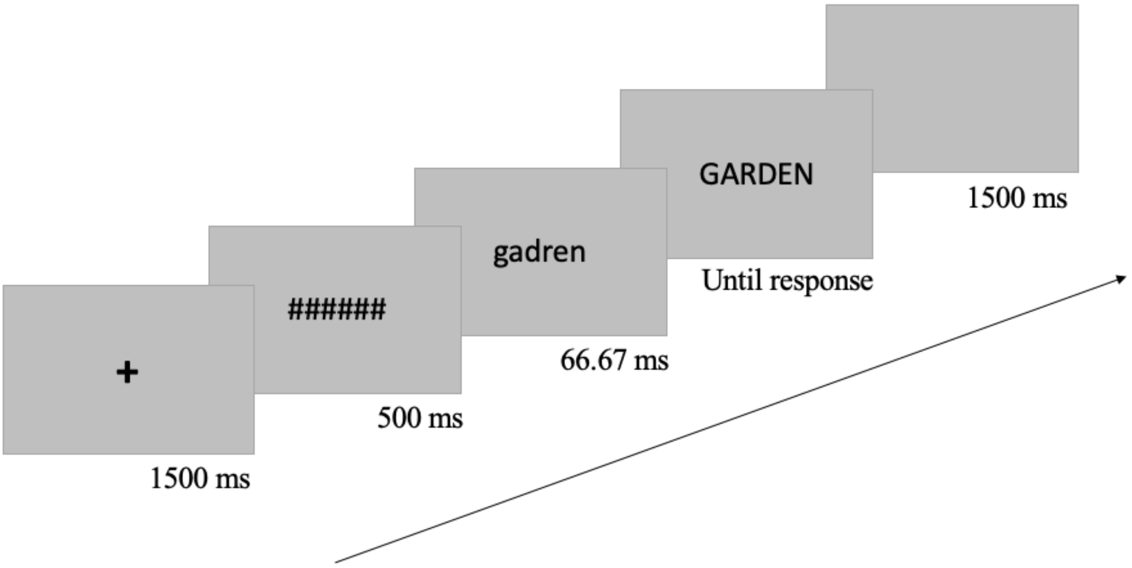


Table 12

Descriptive statistics of accuracies and reaction times per condition and language for Experiment 1 on unimodal TL priming

Condition	**Accuracy in %**	**Reaction times in ms**
TL	97.220	652.518 (166.629)
Repetition	98.679	622.249 (166.352)
Control	97.540	665.949 (156.347)
Language	**Accuracy in %**	**Reaction times in ms**
German (L1)	98.218	641.757 (157.682)
English (L2)	97.443	651.549 (169.875)

Note. Accuracy refers to the percentage of correctly answered trials of all trials. Standard deviation in brackets.

3.2.3 Summary

The results of Experiment 1 show repetition and TL priming effects evident by reduced reaction times for targets preceded by a TL or repetition prime compared to the control condition. Repetition priming effects were also evident in the accuracy data. Because accuracies were overall very high for both languages irrespective of the condition, the lack of a TL priming effect in accuracies could be due to a ceiling effect. For both accuracies and reaction times, net repetition priming effects were stronger than net TL priming effects. Net priming effects also showed a higher TL priming effect in the L1 German compared to the L2 English. However, results of the statistical model did not show an interaction effect between condition and language which indicates that TL and repetition primes influenced their target in similar ways in both languages, irrespective of the acquisition status. Thus, the findings of Experiment 1 replicate previous results of unimodal TL priming and are in accordance with the hypotheses: TL priming effects were found for both the L1 and the L2 but showed stronger effects in the dominant language (Meade, 2022; Perea et al., 2011). Moreover, these results indicate that the stimulus material and the experimental design are suitable to evoke TL priming effects in late German-English bilinguals in both languages.

Table 13

Net TL and repetition priming effects per language of Experiment 1 on unimodal TL priming

German

	TL	**Repetition**	**Control**	**ΔTL-Control**	**ΔRepetition-Control**
Accuracy in %	98.570	98.760	97.323	1.247	1.437
RTs in ms	641.714	620.921	662.885	-21.171	-41.964

English

	TL	**Repetition**	**Control**	**ΔTL-Control**	**ΔRepetition-Control**
Accuracy in %	96.597	98.605	97.125	-0.528	1.480
RTs in ms	662.651	623.475	668.758	-6.107	-45.283

3.3 Experiment 2

In Experiment 2, I sought to extend the previous findings on TL priming by using a cross-modal (visual prime - auditory target) TL priming paradigm. While previous studies have argued that phonological information does not play a role in TL priming effects, the BIAM predicts bimodal activation of orthography and phonology irrespective of the input modality. According to the extended BIAM presented in Figure 11, phonology should be activated by TL primes via bidirectional links between whole-word orthographic and whole-word phonological representations. Following the assumptions of the BIAM, I hypothesize that I can use a visual TL prime to pre-activate an auditory target. Given the effect of spoken words on the activation of orthographic representations (Chérau et al., 2007; Perre et al., 2009) one might expect the mirror-inverted effect for TL primes on auditory targets. In addition, if such an effect (inhibitory or facilitating) occurs the question arises whether it is dependent on the orthographic depth of the target language with German having a shallow and English having a deep orthography. Based on the assumptions and results of my first study and on consideration of the PGST, I hypothesize that the bimodal activation should be more pronounced in English than in German.

3.3.1 Method

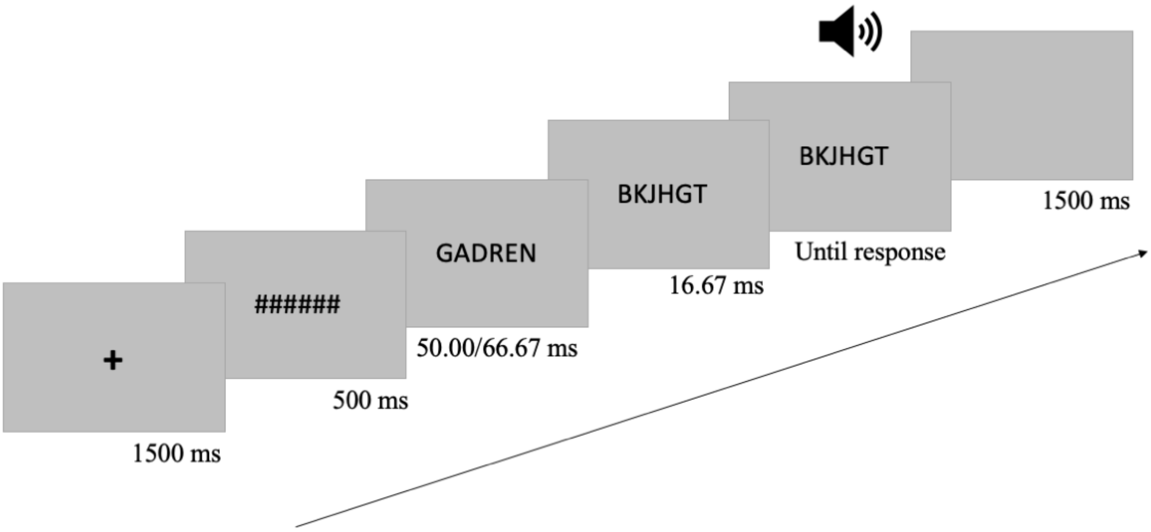
Participants. Sixty participants (44 female, mean age: 24.62 years) without any psychological or neurological issues, or language impairments were recruited via the University's mailing list. All participants were right-handed and reported no hearing impairments and had normal or corrected-to-normal vision. Participants were native German speakers with English as their second language. Mean age of acquisition of English was 9.45 years (*SD* = 1.73, range = 6-14 years). English language proficiency was measured with the LexTALE test. The LexTALE test was administered to all participants after the main experiment. The mean score was 79.81 (*SD* = 13.36) with a range between 43.75 and 100. This corresponds to an upper intermediate to lower advanced level of English. Participants were randomly but counterbalanced assigned to one of the two languages (German or English). Participant age ($t(57.672) < 1$, $p = .970$), age of acquisition of English ($t(53.768) < 1$, $p = .713$) as well as LexTALE scores ($t(56.415) < 1$, $p = .877$) were equal across the two groups.

Material. Stimuli were the same as in Experiment 1. German target stimuli were recorded by a female native speaker of Standard High German and English target stimuli were recorded by a female native speaker of American English in a soundproof booth via an electret microphone (Sennheiser) and a mixing console (Behringer Xenyx X2442) with the recording software Audacity (Audacity Team, 2019). Sound files were normalized in loudness and edited using PRAAT (Boersma & Weenink, 2020). German stimuli had a mean length of 797 ms and English stimuli had a mean length of 753 ms.

Procedure. The experiments were programmed using the Psychophysics Toolbox extension (Brainard, 1997; Kleiner et al, 2007) for Matlab. Reaction time and neurophysiological data were collected simultaneously. The trial scheme was similar to Experiment 1 except that the prime was presented visually in uppercase letters, and the target was presented auditorily. Moreover, to investigate effects of prime visibility on the efficiency of cross-modal TL priming, the prime was presented for 66.67 ms to the first half of the participants and was reduced to 50.00 ms for the second half of the participants. Directly after presentation of the prime, a backward mask consisting of random consonant strings (BKJHGT) was presented. One framerate (16.67 ms) after onset of the backward mask, the target was presented. The backward mask stayed on screen until the end of the trial. The number of letters of the backward mask was equal to the number of letters of the prime. Again, participants had to decide upon hearing the target if the target was a real word or a pseudoword in the respective language. No timeout was set for the decision and no feedback was given during the experiment. Participants were again instructed to answer as quickly and accurately as possible. To avoid eye artifacts, they were instructed only to blink after a response was given. The trial scheme is shown in Figure 13.

Figure 13

Trial scheme of the cross-modal TL priming paradigm



Data recording and pre-processing.

Behavioral data. Data pre-processing of accuracies and reaction times was similar to Experiment 1. Reaction times lower than 350 ms and higher than 3,500 ms were excluded prior to further analysis. This concerned less than one percent of all data points. Prior to the analysis of reaction times, incorrect responses were excluded. This concerned 3.98% of all data points. Cook's distance was below 0.199 for all data points and consequently was lower than a cut-off threshold of $D_i < 1.000$. However, some data points exceeded a cut-off threshold of $D_i < 4/n$. These data points were excluded prior to further analysis. This concerned less than one percent of all data points.

EEG data. The EEG was recorded from 32 active electrodes (actiCAP) placed in an elastic cap (actiCAP) following the 10/20-system at a sampling rate of 500 Hz. Electrodes Fp1 and Fp2 were used to measure horizontal and vertical eye movements.[8] Electrode position FCz was used as the online reference. Impedances were kept below 5kΩ. I used the BrainAmp Standard Amplifier (BrainVision). Averaging was performed offline.

Pre-processing of the neurophysiological data was performed with the EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes for MATLAB (Version 2023a). Data were filtered with a 0.1 Hz high-pass and a 100 Hz low-pass filter, so as not to exclude bands of higher frequency that were of interest for the subsequent TF analysis. EEG data were re-referenced offline to the average of the mastoid electrodes (TP9, TP10). Artifacts were first rejected automatically using ASR with a parameter of 20 times the standard deviation of the calibration data. However, for some of the participants, the cut-off value was adjusted to 40 or 50 times the standard deviation to keep an adequate number of trials for data analysis. Following the ASR, an ICA was performed with the infomax algorithm. Afterwards data were checked manually for remaining artefacts and cleaned if necessary.

Epoching was performed on cleaned data. Only correctly answered trials were considered for further analysis. Rejection rates, thus, included rejection based on incorrect answers and noise. On average 20.54% (*SD* = 13.20%) of the data was rejected. Individual rejection rates ranged from 0% to 50%. At least 50% of trials (25 out of 50) per condition needed to be kept in order to further analyze a dataset. This was the case for all participants. Baseline correction was performed on epoched data. The same baseline was used for ERP and TF measures. I chose the last 400 ms of the fixation cross as the baseline period. This led to epochs of -1000 ms to 1000 ms around the onset of the target stimulus and to a baseline of 40% length of the period of interest. It should be noted that the ITI must be considered the most neutral period in the trial because only a blank screen is presented. However, choosing the ITI as a baseline results in very long epochs which led to high noise and a high level of data discontinuity which in turn led to the exclusion of a lot of trials. This would again constitute an issue for the ITPC calculation as was discussed for study 1. Therefore, a baseline closer to the period of interest was chosen to reduce the length of the necessary epoch. Moreover, the fixation cross ensures attention of the participant to the trial, which reduces influences of non-related brain activity on the ERPs and the TF values and reduced the possibility of eye artifacts. The fixation cross is

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[8] Due to the coronavirus pandemic, I refrained from placing electrodes on the face of the participants in accordance with the safety guidelines of the laboratory, thus EOG was captured with electrodes Fp1 and Fp2.

neither language-related nor does it change across conditions, thus, it was deemed the most appropriate baseline for both ERPs and TF measures.

Time-frequency analysis was performed using EEGLAB and following the methods of Morales and Bowers (2022). TF power and ITPC measures were investigated. TF decomposition was performed with a complex morlet wavelet ranging from three to 10 cycles. Similar to study 1, I analyzed frequencies between 3 and 80 Hz at a resolution of 0.5 Hz increments. Frequencies were then combined to frequency bands in the same way as in study 1: delta (< 5 Hz), theta (5-8 Hz), alpha (8-12 Hz), beta (15-30 Hz) and gamma (30-80 Hz). Subsampling was used to draw 10 trials for 12 subsamples of data to get equal resolution for all conditions.

Data analysis.

Behavioral data. Data analysis was similar to Experiment 1 with the additional fixed effect of prime duration and its interaction with condition included in both statistical models.

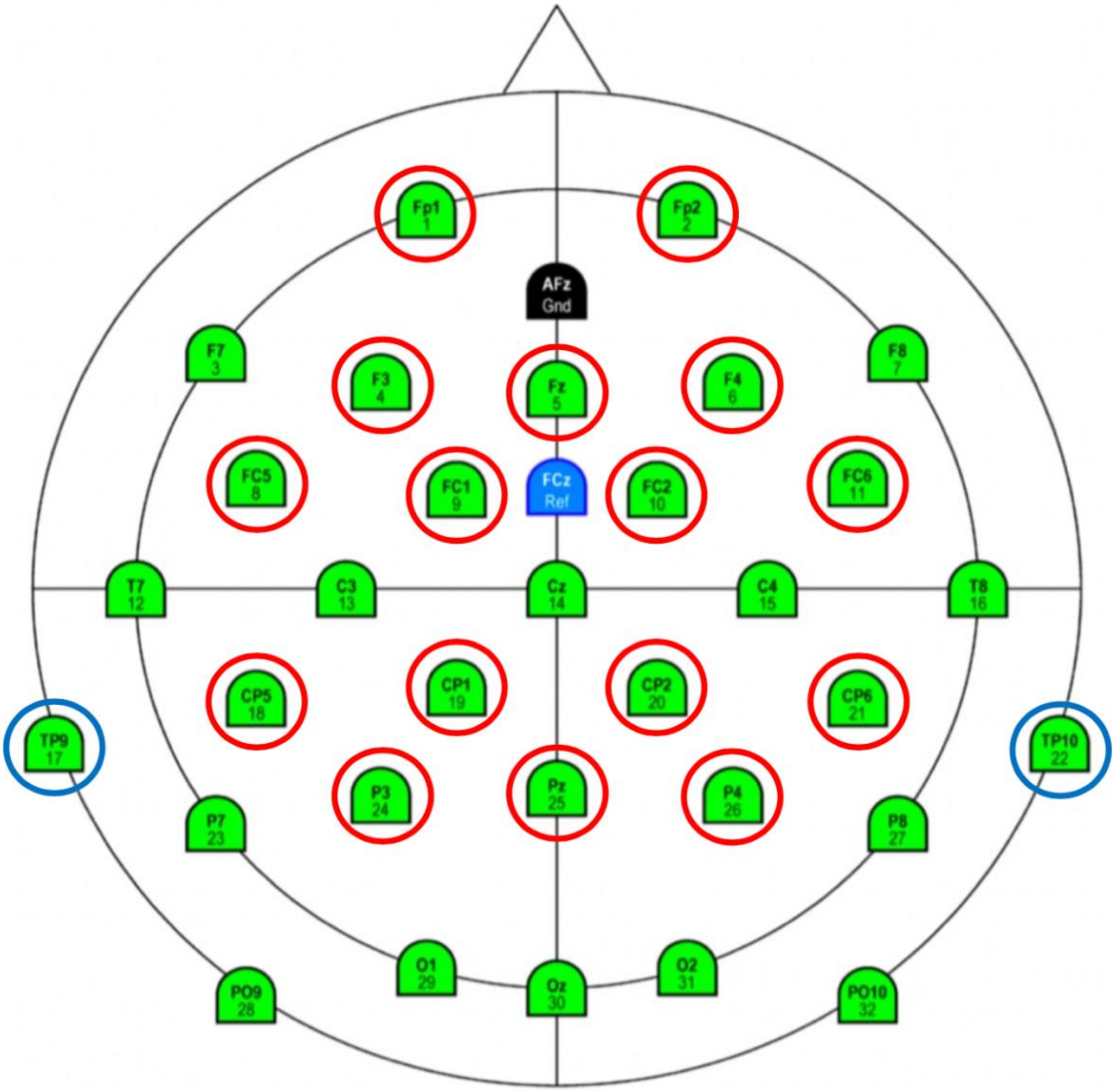
EEG data. Statistical analysis of EEG data is complicated by the high dimensionality of the data. The effect of interest is evaluated over an extremely large number of channels and time points, in this experiment I used 32 channels and 500 time points (excluding the baseline) leading to several thousand (channel, time)-samples. Consequently, statistical analysis faces the multiple comparisons problem: Statistically comparing conditions a large number of times leads to an inflation of the Type I error rate which results in potential false positives, i.e., detecting a significant effect that is not present in reality. Different approaches can be used to account for the inflation of the Type I error rate, the most common of which is the averaging over pre-selected time windows and regions of interest based on previous studies to reduce the number of statistical tests (Luck, 2014). This is especially suitable for replication studies as was the case for study 1. However, this confirmatory approach limits the data analysis to previously investigated temporal and spatial regions and, thus, is not suitable to detect previously unknown effects, which is especially important in a paradigm such as this, which has never been attempted before. As discussed in the introduction, the time-course of activation of orthographic and phonological information in the cross-modal paradigm might well be different than the time-course observed in a unimodal paradigm. Therefore, additionally exploratory analyses are important to detect differences between the two paradigms. A second, statistically sound way to identify relevant time points and regions of interest uses a cluster-based permutation test (CBPT) (Frömer et al., 2018; Maris & Oostenveld, 2007).

CBPT allows the data-driven selection of suitable time windows and regions of interest without *a priori* assumptions. The null hypothesis that different experimental conditions are sampled from the same probability distribution is statistically tested. If the observed effects are highly unlikely under the random assignment of condition labels, the observed difference is considered to be significant. Statistically, a *t*-test is carried out between time points and electrodes of different experimental conditions. If the *t*-value is lower than a given threshold, the difference is considered significant. Neighboring time points and electrodes are often correlated regarding the effects of interest because an experimental manipulation almost always affects more than one electrode and more than one time point. CBPT uses this correlation to identify clusters in both the time and the space domain. Clusters are defined by neighboring channels and time samples that show significant positive or negative *t*-values. The *t*-values of a cluster are added to form a cluster-level statistic. This statistic is compared to the permutation distribution of cluster statistics. The distribution is created by randomly assigning condition labels to data sets and running the same test a large number of times. If the cluster-level statistic of the observed data is larger than 95% of the cluster-level statistics of the permutation distribution, it is considered significant.

I used both, confirmatory and exploratory approaches to data analysis. First, based on previous studies (e.g., Eddy et al. 2016; Grainger et al., 2006; Mead et al., 2020, 2021, 2022), I looked at *a priori* defined time windows of 150 to 300 ms for the N250 and of 350 to 550 ms for the N400. Moreover, I defined regions of interest (ROIs) based on the previous literature in the following way: fronto-polar (Fp1, Fp2, F3, Fz, F4), fronto-central (FC1, FC2, FC5, FC6), centro-parietal (CP1, CP2, CP5, CP6), parietal (P3, Pz, P4). Locations of the electrodes of interest can be seen in Figure 14. However, as cross-modal TL priming had never been investigated before, I also used two exploratory approaches to capture effects outside of these pre-defined time windows and regions of interest. First, I used a cluster-based permutation test as implemented in the EEGLAB toolbox to identify relevant channels and time points for the TL priming and the repetition priming effects based on a data-driven method. Secondly, I used the approach taken in the previous study and investigated consecutive 50 ms epochs between 0 and 600 ms.

Figure 14

Positions of electrodes of interest according to the standardized 10/20 electrode system for study 2



Note. Gnd = ground electrode; Ref = online reference electrode. Indicated in red are electrodes selected for confirmatory analysis. Indicated in blue are the offline reference electrodes.

Confirmatory analyses were carried out using linear mixed effects models (LMMs) in R Studio implemented in the lme4 package. LMMs were run on single-trial EEG data. Mean amplitudes averaged over pre-defined time windows were used as the dependent variable, condition (TL, control, repetition), time window (150-300 ms, 350-550 ms), language (German, English), ROI (fronto-polar, fronto-central, centro-parietal, parietal) and prime duration (50.00 ms, 66.67 ms) were included as fixed effects in the model. Interactions between all fixed effects were implemented. By-subject and by-item random intercepts were included as random effects. Type II Wald-Chi-Square tests were used to test for significance of fixed effects. Planned contrasts with the control as the reference condition were used to test for significant differences between levels of the factor condition. Contrasts were tested against the normal distribution with asymptotic degrees of freedom. Bonferroni correction was applied to account for family-wise error rates. I report the test statistic, the *p*-value as well as the respective effect size (R^2, *d*) for significant effects.

Permutation tests using the Monte Carlo method with 500 permutations and an alpha level of .100 was used to test for spatial and temporal clusters in the data[9]. This test is implemented in the EEGLAB toolbox and uses FieldTrip (Oostenveld et al., 2011) functions. The cluster-based correction for multiple comparisons was used to correct for family-wise error rates as recommended by Maris and Oostenveld (2007). Instead of using multiple comparisons of (sample, time)-pairs and correcting for the number of comparisons, a cluster is defined based on adjacent electrodes and time points that are correlated. Once a cluster is defined, a cluster-based statistic is used to test for significance. Thus, only one comparison using the cluster-level statistic is needed, avoiding the multiple-comparisons problem and is assumed to be less conservative than common correction methods such as Bonferroni. Neighboring electrodes were automatically defined based on channel locations derived from the channel labels using the triangulation method. The cluster-level statistics used was the maximum of the cluster-level summed *t*-values. Within-subject permutation tests were carried out separately per group and prime duration.

Furthermore, I analyzed consecutive 50 ms epochs between 0 and 600 ms after target onset. LMMs with the fixed factors condition (TL, repetition, control), language (German, English), epoch and prime duration (66.67 ms, 50.00 ms) and by-subject and by-item random intercepts were used on single-trial data including 30 electrodes. The offline references TP9 and TP10 were excluded prior to analysis. Note that neither channel nor ROI was used as a fixed factor, because the resulting matrix was too large for lme4 to compute. Thus, no ROIs or channels were pre-selected for analysis. Consequently, results are averaged over channels. Hence, the analysis only gives answers about the time-course of effects, but not about regions of interest. Significance of fixed effects was tested with Type II Wald-Chi-Square tests. Planned contrasts were used as post-hoc tests with Bonferroni correction to control for family-wise error rates. Contrasts were tested against the normal distribution with asymptotic degrees of freedom.

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[9] An alpha level of .100 was used in order to not disregard effects that did not reach the conventional .05 significance level but could be defined as “marginally significant”. However, this makes the test less conservative and increases the Type I error.

Table 14

Descriptive statistics of accuracies and reaction times per condition, prime duration and language for Experiment 2 on cross-modal TL priming

Condition	Accuracies in %	Reaction times in ms
TL	96.226	920.699 (204.735)
Repetition	95.993	914.851 (203.868)
Control	95.854	937.915 (206.904)
Prime duration	**Accuracies in %**	**Reaction times in ms**
66.67 ms	96.109	922.944 (216.083)
50.00 ms	95.940	925.994 (194.058)
Language	**Accuracies in %**	**Reaction times in ms**
German (L1)	98.311	899.774 (192.051)
English (L2)	93.729	950.486 (215.530)

Note. Accuracy refers to the proportion of correctly answered trials of all trials. Standard deviation in brackets.

I used TF measures additionally to ERPs to find out more about the cognitive mechanisms underlying the processes of interest. To reduce the number of statistical tests, I investigated TF measures for the N250 and N400 ERP components. I used the same time windows and ROIs as in the confirmatory ERP analysis. TF values were averaged over time windows and analyzed with LMMs including condition (TL, repetition, control), time window (N250, N400), frequency band (delta, theta, alpha, beta, gamma), ROI (fronto-polar, fronto-central, centro-parietal, parietal), prime duration (66.67 ms, 50.00 ms) and language (German, English) as fixed effects and by-subject random intercepts. Note that TF measures were not computed on a trial-by-trial basis. Thus, by-item random intercepts could not be included in the model. Significance of fixed-effects was computed via Type II Wald-Chi square tests. Planned contrasts with the control condition as the reference condition were used as post-hoc tests for condition. Bonferroni correction was applied to account for family-wise error rates. Contrasts were tested against the normal distribution with asymptotic degrees of freedom. Effect sizes were again calculated with the MuMIn and the emmeans packages. The test statistic, the *p*-value and the effect size for significant effects are reported.

3.3.2 Results

3.3.2.1 Behavioral results. The logistic mixed effects model for accuracies showed a main effect of language ($W(1) = 15.229$, $p < .001$, $R^2 = 0.073$). Accuracies were higher for the L1 German compared to the L2 English. The interaction between condition and language ($W(2) = 7.307$, $p = .026$, $R^2 = 0.083$) also reached significance. Neither the main effect of prime duration ($W(1) < 1$, $p = .807$) nor the interaction between prime duration and condition ($W(2) = 1.008$, $p = .604$) reached significance. Subsequent analyses showed a significant repetition priming effect ($z = 2.260$, $p = .048$, $d = 0.697$) and a significant TL priming effect ($z = 2.306$, $p = .042$, $d = 0.716$) for the German group. For the English group, no significant effect of condition was found ($W(2) < 1$, $p = .768$). The linear mixed effects model for reaction times revealed a main effect of condition ($W(2) = 43.381$, $p < .001$, $R^2 = .003$) and a main effect of language ($W(1) = 4.466$, $p = .035$, $R^2 = 0.020$). None of the other effects reached significance. Reaction times were lower for the L1 German compared to the L2 English. Post-hoc planned contrasts revealed a significant difference between the repetition priming and the control condition ($z = 6.223$, $p < .001$, $d = 0.165$) and between the TL priming condition and the control condition ($z = 4.946$, $p < .001$, $d = 0.131$). An overview of descriptive statistics can be seen in Table 14. Net priming effects are shown in Table 15.

3.3.2.2 ERP results.

Confirmatory analysis. In the following, only significant effects of interest, i.e., the highest interactions involving the factor condition are reported. The overall model showed significant main effects of condition ($W(2) = 31.574$, $p < .001$, $R^2 = 1.283 \cdot 10^{-4}$), ROI ($W(3) = 661.072$, $p < .001$, $R^2 = 2.684 \cdot 10^{-3}$) and time window ($W(1) = 3084.299$, $p < .001$, $R^2 = 1.253 \cdot 10^{-2}$). The four-way interaction between condition, language, time window and prime duration ($W(2) = 9.412$, $p = .009$, $R^2 = 1.612 \cdot 10^{-2}$) was also significant. Subsequently, the four-way interaction was further analyzed by looking at the two prime durations separately. For the longer prime duration of 66.67 ms, main effects of condition ($W(2) = 108.905$, $p < .001$, $R^2 = 8.725 \cdot 10^{-4}$), of ROI ($W(3) = 560.996$, $p < .001$, $R^2 = 4.462 \cdot 10^{-3}$) and of time window ($W(1) = 1587.261$, $p < .001$, $R^2 = 1.264 \cdot 10^{-2}$) were found. The three-way interaction between condition, language and time window ($W(2) = 17.866$, $p < .001$, $R^2 = 2.009 \cdot 10^{-2}$) also reached significance.

Table 15

Net TL and repetition priming effects per language and prime duration of Experiment 2 on cross-modal TL priming

German

66.67 ms

	TL	Repetition	Control	ΔTL-Control	ΔRepetition-Control
Accuracies in %	98.800	98.800	97.597	1.203	1.203
RTs in ms	884.608	880.673	906.054	-21.446	-25.381

50.00 ms

	TL	Repetition	Control	ΔTL-Control	ΔRepetition-Control
Accuracies in %	98.533	98.533	97.600	0.933	0.933
RTs in ms	902.223	904.922	920.530	-18.307	-15.608

English

66.67 ms

	TL	Repetition	Control	ΔTL-Control	ΔRepetition-Control
Accuracies in %	94.259	93.333	93.859	0.400	-0.526
RTs in ms	957.190	946.796	967.584	-10.394	-20.788

50.00 ms

	TL	Repetition	Control	ΔTL-Control	ΔRepetition-Control
Accuracies in %	93.289	93.289	94.347	-1.058	-1.058
RTs in ms	941.808	929.630	959.705	-17.897	-30.075

For the N250 time window (150-300 ms), main effects of condition ($W(2) = 63.525$, $p < .001$, $R^2 = 1.020 \cdot 10^{-3}$) and of ROI ($W(3) = 141.807$, $p < .001$, $R^2 = 2.241 \cdot 10^{-3}$) were found. The interaction between condition and language ($W(2) = 23.975$, $p < .001$, $R^2 = 7.273 \cdot 10^{-3}$) also reached significance. The three-way interaction between condition, ROI and language ($W(6) = 3.183$, $p = .786$) did not reach significance. Subgroup analyses showed a significant main effect of condition ($W(2) = 6.003$, $p = .050$, $R^2 = 1.811 \cdot 10^{-4}$) and a significant main effect of ROI ($W(3) = 122.292$, $p < .001$, $R^2 = 3.623 \cdot 10^{-3}$) for the German group. The interaction between condition and ROI ($W(6) = 4.117$, $p = .661$) did not reach significance. Contrasts showed a significant difference between the TL and the control condition ($z = 2.245$, $p = .050$, $d = 0.305$), but not between the repetition and the control condition ($z < 1$, $p = 1.000$). For the English group, main effects of condition ($W(2) = 89.098$, $p < .001$, $R^2 = 2.999 \cdot 10^{-3}$) and of ROI ($W(3) = 36.489$, $p < .001$, $R^2 = 1.171 \cdot 10^{-3}$) were significant, but the interaction did not reach significance ($W(6) = 1.130$, $p = .980$). Contrasts revealed a significant difference between the TL and the control condition ($z = 7.363$, $p < .001$, $d = 0.116$), but not between the repetition and the control condition ($z = -1.224$, $p = .442$).

For the N400 time window (350-550 ms), main effects of condition ($W(2) = 61.697$, $p < .001$, $R^2 = 9.952 \cdot 10^{-4}$) and of ROI ($W(3) = 482.458$, $p < .001$, $R^2 = 7.673 \cdot 10^{-3}$) were found. The main effect of language was marginally significant ($W(1) = 2.752$, $p = .097$, $R^2 = 6.778 \cdot 10^{-3}$). The interaction between condition and language ($W(2) = 40.666$, $p < .001$, $R^2 = 3.314 \cdot 10^{-3}$) was also significant. Subgroup analyses showed a significant main effect of condition ($W(2) = 63.271$, $p < .001$, $R^2 = 1.847 \cdot 10^{-3}$) and a main effect of ROI ($W(3) = 215.467$, $p < .001$, $R^2 = 6.214 \cdot 10^{-3}$) for the German group. The interaction between condition and ROI ($W(6) = 4.125$, $p = .660$) did not reach significance. Contrasts showed significant differences between the TL and the control condition ($z = 6.614$, $p < .001$, $d = 0.097$) and between the repetition and the control condition ($z = 7.331$, $p < .001$, $d = 0.106$). As can be seen in Figure 15, the control condition showed a significantly more negative-going wave form than both primed conditions. For the English group, a main effect of condition ($W(2) = 43.949$, $p < .001$, $R^2 = 1.523 \cdot 10^{-3}$) and a main effect of ROI ($W(3) = 286.145$, $p < .001$, $R^2 = 9.572 \cdot 10^{-3}$) were found. The interaction between condition and ROI ($W(6) < 1$, $p = .986$) did not reach significance. Contrasts revealed a significant difference between the TL and the control condition ($z = 4.348$, $p < .001$, $d = 0.069$) and a marginally significant effect for the repetition condition ($z = -2.129$, $p = .067$, $d = 0.034$). Remarkably, the latter effect was in the opposite direction than expected with the repetition condition showing more negative values than the control condition.

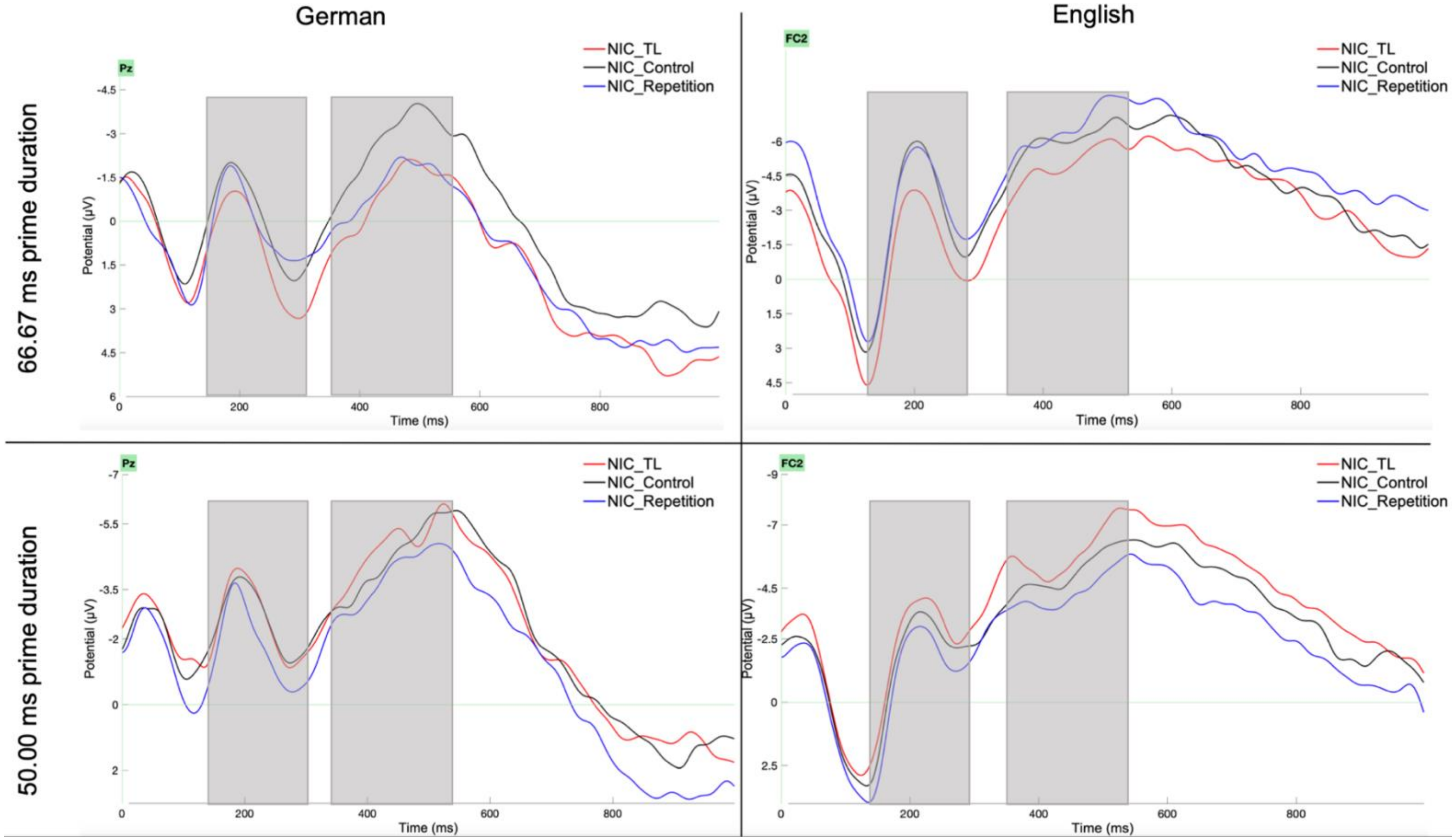
For the shorter prime duration of 50.00 ms, a main effect of condition ($W(2) = 93.306$, $p < .001$, $R^2 = 7.663 \cdot 10^{-4}$), a main effect of ROI ($W(3) = 169.172$, $p < .001$, $R^2 = 1.365 \cdot 10^{-3}$) and a main effect of time window ($W(1) = 1528.438$, $p < .001$, $R^2 = 1.234 \cdot 10^{-2}$) were found. The interaction between condition and language ($W(2) = 9.160$, $p = .010$, $R^2 = 1.110 \cdot 10^{-3}$) also reached significance. None of the other interactions involving the factor condition reached significance. For the German group, a main effect of condition ($W(2) = 29.245$, $p < .001$, $R^2 = 4.958 \cdot 10^{-4}$), a main effect of time window ($W(1) = 1499.426$, $p < .001$, $R^2 = 2.463 \cdot 10^{-2}$) and a main effect of ROI were found ($W(3) = 35.142$, $p < .001$, $R^2 = 5.772 \cdot 10^{-4}$). None of the interactions involving condition reached significance. Planned contrasts revealed a significant difference between the repetition and the control condition ($z = 3.797$, $p < .001$, $d = 0.042$), but no difference between the TL and the control condition ($z = -1.169$, $p = .485$) was found. For the English group, a significant main effect of condition ($W(2) = 73.708$, $p < .001$, $R^2 = 1.175 \cdot 10^{-3}$), of time window ($W(1) = 342.327$, $p < .001$, $R^2 = 5.257 \cdot 10^{-3}$) and of ROI ($W(3) = 348.814$, $p < .001$, $R^2 = 5.356 \cdot 10^{-3}$) were found. None of the interactions involving condition reached significance. Planned contrasts showed a significant difference between the TL and the control condition ($z = -5.083$, $p < .001$, $d = 0.013$) and between the repetition and the control condition ($z = 3.494$, $p = .001$, $d = 0.042$). Here the TL priming effect showed the opposite direction than expected with the TL condition having more negative values than the control condition.

Cluster-based permutation test. For the German group at a prime duration of 66.67 ms, permutation tests revealed a large spatial cluster consisting of electrodes Fz, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8 and Oz for the repetition priming condition compared to the control condition. Temporal clusters started at around 500 ms post-stimulus onset and lasted until 600 ms post stimulus onset. For the TL condition, no significant spatial cluster was found. Subsequent inspection of single electrodes revealed a temporal cluster starting at around 450 ms and lasting about 50 ms at electrode P4. For the English group at a prime duration of 66.67 ms, no significant spatial clusters were found for the repetition priming effect. Temporal clusters were found very early starting at 0 ms and lasting about 20 ms at electrode CP5 and late clusters were found starting at about 550 ms for electrodes FT9 and FT10 and lasting until 600 ms. For the TL priming effect, again, no spatial clusters could be identified. Temporal clusters were found at electrodes F3 and FC5 starting around 200 ms and lasting about 50 ms and at electrode Fp1 starting around 50 ms and lasting up until 350 ms.

For the German group at 50.00 ms prime duration, no significant spatial clustering could be identified for the repetition priming effect. A very early temporal cluster starting at around 20 ms could be found for electrode P7. No other temporal clusters were found. For the TL priming effect, no spatial clusters were observed. Temporal clustering started at about 100 ms and lasted up to about 350 ms at electrode Fp1. For the English group at 50.00 prime duration, no spatial clusters could be observed for the repetition priming effect. A temporal cluster could be found starting at around 150 ms at electrode Oz. For the TL condition, no spatial clusters were observed. Temporal clusters could be found starting at around 50 ms at electrodes F8 and FT10.

Figure 15

Grand-average ERPs of Experiment 2 on cross-modal TL priming



Note. Negativities are plotted upwards. NIC = non-identical cognate, TL = transposed letter. Grand-average ERPs were calculated group-wise for German (left) and English (right) as the target language as well as for a prime duration of 66.67 ms (top) and 50.00 ms (bottom). Relevant time windows are indicated in grey (N250: 150-300 ms; N400: 350-550 ms). A 10 Hz filter was applied for visualization purposes.

Consecutive 50 ms analysis. The overall model showed a main effect of condition ($W(2) = 80.854$, $p < .001$, $R^2 = 3.096 \cdot 10^{-5}$) and a main effect of epoch ($W(11) = 44{,}464.266$, $p < .001$, $R^2 = 1.687 \cdot 10^{-2}$). The interaction between condition and epoch ($W(22) = 108.435$, $p < .001$, $R^2 = 1.694 \cdot 10^{-2}$), between condition and language ($W(2) = 275.229$, $p < .001$, $R^2 = 1.384 \cdot 10^{-4}$) and between condition and prime duration ($W(2) = 878.493$, $p < .001$, $R^2 = 7.140 \cdot 10^{-4}$) also reached significance. The three-way interactions between condition, epoch and language ($W(22) = 185.894$, $p < .001$, $R^2 = 1.775 \cdot 10^{-2}$), between condition, epoch and prime duration ($W(22) = 138.689$, $p < .001$, $R^2 = 1.801 \cdot 10^{-2}$) and between condition, language and prime duration ($W(2) = 376.738$, $p < .001$, $R^2 = 4.067 \cdot 10^{-3}$) were significant. The four-way interaction between condition, epoch, language and prime duration ($W(22) = 211.751$, $p < .001$, $R^2 = 2.241 \cdot 10^{-2}$) was also significant. Results of subsequent analyses are shown in Table 16.

Table 16

Results of consecutive 50 ms epochs between 0 and 600 ms averaged over 30 electrodes for Experiment 2 on cross-modal TL priming

66.67 ms prime duration				
	TL priming effect		**Repetition priming effect**	
Epoch (ms)	**German**	**English**	**German**	**English**
0-50	< .001	< .010	< .050	< .001
50-100	-	< .001	-	< .001
100-150	-	< .001	< .001	< .001
150-200	-	< .001	-	-
200-250	-	< .001	-	< .100
250-300	< .001	< .001	< .100	< .001
300-350	< .001	< .001	< .010	< .010
350-400	< .001	-	< .001	< .001
400-450	< .001	< .010	< .001	< .001
450-500	< .001	-	< .001	< .001
500-550	< .001	< .001	< .001	< .001
550-600	< .001	< .010	< .001	< .001

50.00 ms prime duration				
	TL priming effect		**Repetition priming effect**	
Epoch (ms)	**German**	**English**	**German**	**English**
0-50	-	< .001	-	-
50-100	-	< .050	< .050	< .050
100-150	-	< .001	< .001	-
150-200	< .001	< .001	-	-
200-250	-	< .001	< .001	-
250-300	-	-	< .001	< .001
300-350	-	< .001	< .050	-
350-400	-	< .001	< .001	< .100
400-450	< .001	< .001	< .050	< .050
450-500	-	< .050	-	< .001
500-550	-	< .001	-	< .010
550-600	< .050	< .010	< .001	< .001

3.3.2.3 TF results.

The following table gives an overview of all TF effects found for Experiment 2 on cross-modal transposed letter priming. A comprehensive description of all statistical results can be found in Appendix B.

Table 17

Overview of TF results of Experiment 2 on cross-modal TL priming

66.67 ms prime duration					
N250 time window					
Power					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Repetition > control	delta	fronto-polar fronto-central	Repetition < control TL > control	delta	centro-parietal
TL < control	delta	centro-parietal parietal	TL > control	delta	parietal
Primed > control	theta	fronto-polar fronto-central	TL > control	theta	fronto-central

Repetition > control	theta	centro-parietal	Primed > control	theta	centro-parietal parietal
TL < control	alpha	parietal	Primed > control	alpha	fronto-polar fronto-central centro-parietal parietal
Primed < control	beta	fronto-polar fronto-central centro-parietal	TL > higher	beta	fronto-polar
TL < control	beta	parietal	Primed > control	beta	fronto-central centro-parietal parietal
Repetition > control	gamma	fronto-polar parietal	Primed < control	gamma	fronto-polar fronto-central parietal
TL < control	gamma	fronto-central	Repetition < control TL > control	gamma	centro-parietal

ITPC

German			English		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
TL > control	delta	fronto-central	TL > control	delta	fronto-central
Repetition < control	delta	centro-parietal parietal	Repetition > control	delta	parietal
TL > control	theta	fronto-polar fronto-central	Repetition < control	theta	fronto-polar fronto-central
Repetition < control TL > control	theta	centro-parietal	TL > control	theta	parietal
Repetition < control	theta	parietal			
Primed > control	alpha	fronto-polar fronto-central	Primed < control	alpha	fronto-polar fronto-central
			Repetition < control	alpha	centro-parietal
			Repetition < control TL > control	alpha	parietal
Repetition > control	beta	fronto-central	Repetition < control TL > control	beta	fronto-polar parietal
TL < control	beta	centro-parietal parietal	Repetition < control	beta	fronto-central centro-parietal
Primed < control	gamma	fronto-polar	Repetition < control	gamma	fronto-polar
Repetition > control	gamma	centro-parietal	Primed < control	gamma	fronto-central
			TL < control	gamma	centro-parietal

Repetition > control TL < control	gamma	parietal	Repetition > control TL < control	gamma	parietal
N400 time window					
Power					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Repetition > control	delta	fronto-polar fronto-central	Repetition > control	delta	fronto-polar
TL < control	delta	centro-parietal			
Primed > control	theta	fronto-polar fronto-central	Primed > control	theta	fronto-central centro-parietal parietal
Primed < control	alpha	fronto-polar fronto-central parietal	Repetition < control TL > control	alpha	fronto-polar
			TL > control	alpha	fronto-central
			Primed > control	alpha	centro-parietal parietal
Repetition > control TL < control	beta	fronto-polar fronto-central centro-parietal parietal	Primed < control	beta	fronto-polar
			Repetition < control	beta	fronto-central
			TL > control	beta	centro-parietal parietal
Repetition > control	gamma	fronto-polar	Primed < control	gamma	fronto-polar fronto-central parietal
Repetition > control TL < control	gamma	fronto-central centro-parietal parietal	Repetition < control	gamma	centro-parietal
ITPC					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
TL > control	delta	fronto-polar	Primed > control	delta	fronto-polar centro-parietal parietal
Repetition < control	delta	centro-parietal parietal	TL > control	delta	fronto-central
Repetition < control	theta	fronto-polar fronto-central	Repetition < control	theta	fronto-polar

			Repetition < control TL > control	theta	fronto-central
TL > control	theta	centro-parietal	TL > control	theta	centro-parietal
Primed > control	alpha	fronto-central parietal	TL > control	alpha	fronto-polar fronto-central
			Repetition < control	alpha	centro-parietal
			Repetition < control TL > control	alpha	parietal
Repetition < control	beta	fronto-polar	Repetition > control	beta	fronto-polar
TL > control	beta	centro-parietal			
Primed > control	beta	parietal	Primed > control	beta	parietal
			Repetition < control TL > control	gamma	fronto-polar
TL > control	gamma	fronto-central parietal	TL > control	gamma	fronto-central
Primed > control	gamma	centro-parietal	Primed > control	gamma	centro-parietal parietal
50.00 ms prime duration					
N250 time window					
Power					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
TL > control	delta	fronto-polar fronto-central	Primed > control	delta	fronto-polar fronto-central
Primed > control	delta	centro-parietal parietal	TL > control	delta	centro-parietal
Repetition < control	theta	fronto-polar	TL > control	theta	fronto-polar
Repetition < control TL > control	theta	fronto-central	Repetition < control TL > control	theta	fronto-central
TL > control	theta	centro-parietal parietal	TL > control	theta	centro-parietal
TL > control	alpha	fronto-polar fronto-central centro-parietal	TL < control	alpha	fronto-central
Primed > control	alpha	parietal	Repetition > control TL < control	alpha	centro-parietal parietal

Primed < control	beta	fronto-polar fronto-central	Primed > control	beta	fronto-polar fronto-central centro-parietal parietal
TL > control	beta	centro-parietal parietal			
Repetition < control	gamma	fronto-polar	Primed > control	gamma	fronto-polar centro-parietal parietal
Primed < control	gamma	fronto-central centro-parietal parietal	Repetition > control	gamma	fronto-central
ITPC					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Primed > control	delta	fronto-polar	TL > control	delta	fronto-polar
Repetition > control	delta	fronto-central centro-parietal parietal	Repetition < control	delta	fronto-central centro-parietal parietal
Repetition > control	theta	parietal	TL > control	theta	fronto-polar fronto-central
			Primed < control	theta	parietal
Repetition > control	alpha	fronto-polar fronto-central centro-parietal parietal	Primed > control	alpha	fronto-polar
			Repetition > control	alpha	centro-parietal
			TL > control	alpha	parietal
Primed < control	beta	fronto-polar fronto-central	Primed > control	beta	fronto-polar fronto-central parietal
Repetition < control	beta	centro-parietal parietal	TL > control	beta	centro-parietal
Primed > control	gamma	fronto-polar fronto-central parietal	TL < control	gamma	fronto-polar fronto-central centro-parietal
TL > control	gamma	centro-parietal	Primed < control	gamma	parietal
N400 time window					
Power					
German			**English**		

Effect	Band	ROI	Effect	Band	ROI
Repetition > control	delta	centro-parietal	Repetition < control TL > control	delta	fronto-polar fronto-central centro-parietal
Primed > control	delta	parietal	Repetition < control	delta	parietal
Primed < control	theta	fronto-polar fronto-central	Repetition < control TL > control	theta	fronto-polar parietal
Primed > control	theta	parietal	Repetition < control	theta	fronto-central centro-parietal
Repetition < control TL > control	alpha	fronto-polar fronto-central	Repetition < control	alpha	fronto-polar
TL > control	alpha	centro-parietal	Primed < control	alpha	fronto-central
Primed > control	alpha	parietal	Repetition > control TL < control	alpha	centro-parietal
Primed < control	beta	fronto-polar fronto-central	Repetition > control	beta	fronto-polar fronto-central centro-parietal parietal
Primed > control	beta	parietal			
Repetition > control	beta	centro-parietal			
Primed < control	gamma	fronto-polar fronto-central centro-parietal parietal	TL < control	gamma	fronto-polar fronto-central
			Primed < control	gamma	parietal

ITPC

German			English		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Primed > control	delta	fronto-polar fronto-central	TL < control	delta	fronto-polar fronto-central
TL > control	theta	fronto-polar	Primed > control	theta	fronto-polar fronto-central centro-parietal
Repetition > control TL < control	theta	centro-parietal	Repetition > control	theta	parietal
Repetition > control	theta	parietal			
Repetition > control	alpha	fronto-polar fronto-central centro-parietal	Primed < control	alpha	fronto-polar

Primed > control	alpha	parietal	Repetition > control	alpha	fronto-central centro-parietal
Primed < control	beta	fronto-polar fronto-central	Repetition > control	beta	fronto-polar
Repetition < control	beta	centro-parietal parietal	Primed > control	beta	fronto-central
TL > control	gamma	fronto-polar	Primed < control	gamma	fronto-polar fronto-central
Repetition > control	gamma	centro-parietal			
Primed > control	gamma	parietal			

Note. TL = transposed letter prime.

3.3.3 Summary

The goal of Experiment 2 was to provide for the first time evidence for cross-modal (visual prime – auditory target) TL priming effects in late German-English bilinguals. If word processing is bimodal in nature as assumed by the BIAM, it should be possible to prime an auditory target word with a visual TL prime. Prime duration was manipulated to investigate the effects of prime visibility on priming efficacy. The results corroborate the assumptions and replicate the findings of Experiment 1. Behavioral data indicates significant TL and repetition priming effects apparent as higher accuracies and reduced reaction times for the TL and repetition condition compared to an orthographic control condition in German. In English, this effect was limited to reaction times but showed the same pattern. Similar to Experiment 1, TL priming effects were larger in the dominant language German than in the L2 English.

For the longer prime duration of 66.67 ms, ERPs in the N250 time window indicated significant TL priming for German and English apparent as a reduced N250 amplitude for the TL condition compared to the orthographic control condition. No differences between the repetition and the control condition were found for either language in this time window. Interactions between condition and ROI did not reach significance indicating that the effects were broadly distributed over all investigated electrodes. In the N400 time window, both TL and repetition priming effects were found for the German group apparent as reduced N400 amplitudes for the primed conditions relative to an orthographic control condition. TL and repetition priming effects were also found for the English group; however, the repetition priming effect showed a more negative-going waveform than the control condition.

Exploratory analyses confirm these findings. The cluster-based permutation test (CBPT) revealed a large spatial cluster for the repetition priming effect which shows that this effect was broadly distributed with no clear localization at a specific ROI. Temporal clusters only started at around 500 ms indicating a late effect of repetition priming. The successive 50 ms analysis of ERPs showed some early effects of repetition priming in an epoch of 0 to 50 ms and 100 to 150 ms for the German group. However, a continuous repetition priming effect was only found from 300 ms onwards, which can explain why no effect was found in the N250 time window. For the English group, no spatial clusters could be found for either effect. Temporal clusters indicated a very early effect for repetition priming at 0 ms and a later effect starting around 550 ms. The consecutive 50 ms analysis also showed some early effects. A sustained repetition priming effect was found from 250 ms onwards. For the TL effect, no spatial clusters were found for the German group. Temporal clusters started at around 450 ms. The consecutive 50 ms analysis showed an onset of TL effects from 250 ms onwards. For the English group, temporal clusters started around 50 ms and lasted until 350 ms. The consecutive analysis of 50 ms epochs also indicated a long-lasting early effect of TL priming in English starting at the earliest epoch and lasting until 300 ms. This indicates that TL priming affects spoken word recognition at an earlier point in time than repetition priming and takes place at a sub-lexical level in epochs way before latencies connected to lexical access.

TF results showed overall higher delta band activity for primed conditions compared to the control condition in both languages and time windows with some inconsistencies. This was more pronounced for the repetition condition in German, but for the TL condition in English. Increases in delta band activity have also been observed for the primed conditions in study 1 and have been attributed to higher cognitive engagement with primed conditions relative to unprimed conditions. This is in line with the current findings. Moreover, the results indicate that cognitive engagement was higher for the repetition condition in German, but for the TL condition in English. This could indicate higher relevance for orthographic information during spoken word recognition in English than in German.

In general, higher power and ITPC in the theta band were found for the primed conditions relative to the unprimed condition for both languages and time windows, however, some decreases in ITPC were found for the repetition priming condition. In study 1, the opposite pattern was found. Theta band activity is related to lexical-semantic processing, thus a decrease in theta band activity has previously been attributed to facilitated lexical access for the primed conditions compared to an unprimed condition. This should also be the case in the present study. Theta band synchronization has been reported for word and sentence level processing in contexts that require semantic integration (Bastiaansen et al., 2002, 2005, 2008). Bastiaansen et al. (2005) report that word presentation overall elicits a theta power increase, however, the words in their study were embedded in sentences as well. Semantic integration is unlikely to be the cause in the present study because no semantic judgement was required, and priming was not semantic in nature. Theta band increases have also been observed for visual working memory (Pavlov & Kotchoubey, 2020). Thus, increases in theta band activity might stem from integrating the visual prime from working memory and the target encountered auditorily. This might be prevalent in cross-modal studies. The decreases in ITPC found for the repetition priming condition might indicate some repetition suppression taking place for the presentation of identical items.

In a similar manner, the results show increases in alpha band activity for primed conditions relative to unprimed conditions. These were more pronounced for English relative to German and more pronounced for the TL condition compared to the repetition condition. Activity in the alpha band is connected to inhibitory processes and disengagement of attention. In the previous study, I have found decreases for the primed conditions compared to the unprimed condition and have argued that this indicates higher attention towards targets that show similarities with the prime words. However, similarly to theta band activation, alpha band synchronization has been connected to visual and verbal short-term working memory. Increases in alpha band activity are said to reflect inhibition of task-irrelevant information and interfering representations and has been found to increase for meaningful stimuli relative to control items (Johnson et al., 2011; van Dijk et al., 2010).

Beta band related activity showed a striking pattern: Beta band desynchronization was observed for primed conditions in German, but synchronization was found in English. This was most apparent for beta power and more pronounced for the TL condition. Beta band desynchronization has been observed for the processing of German words relative to pseudowords and has been connected to activation of grapheme-phoneme-correspondences. Klimesch et al. (2001) compared word and pseudoword reading in German dyslexic and non-dyslexic children. They found beta desynchronization for words relative to pseudowords only in non-dyslexic participants. Interestingly, the effects were most pronounced at electrodes FC5, CP5 and P3, which correspond to the fronto-central, centro-parietal and parietal ROIs in the current study. Differences in beta band activity between German and English were found in these ROIs. Strikingly, Klimesch et al. (2001) attribute the FC5 to “Broca’s area” which corresponds to the left IFG. Electrodes CP5 and P3 are associated with the angular gyrus. In the General Introduction, I have identified the left IFG as a region whose activation is especially affected by the orthographic depth of the target language. Activation in this region is found to be higher for deep orthographies relative to shallow orthographies and is connected to grapheme-phoneme-mapping. Thus, higher beta band activity for the TL condition in the

English group could be connected to higher activity in the left IFG. The angular gyrus has been identified to be specifically relevant for cross-modal integration of orthography and phonology in a study conducted in English (Booth et., 2004). Thus, the differences observed in beta band activity might indicate activation differences in the left IFG and angular gyrus between German and English, connected to grapheme-phoneme-conversion and orthographic-phonological mapping, respectively.

Activation in the gamma band was rather unspecific and showed effects in both directions with power and ITPC exhibiting often contradictory results. Thus, it seems hard to identify a clear pattern and draw conclusions from these findings. It is particularly striking, though, that gamma phase synchrony often shows increases for the repetition condition in both languages. This frequency band has previously been connected to repetition suppression, meaning a decrease in neural activity for items that are repeated. Consequently, a decrease in neural activation in the gamma frequency band should be expected specifically for the repetition condition, because here the identical item is shown twice. It might be possible that the repetition suppression effect is less effective in a cross-modal paradigm because the item is not repeated in the same modality. However, to my knowledge, no studies on cross-modal repetition suppression have yet been conducted.

For the shorter prime duration of 50.00 ms, the interactions between condition and time window were not significant indicating comparable effects in both time windows. For the German group, only a repetition priming effect was found. The CBPT only showed a spurious effect at 20 ms for the repetition condition. Temporal clusters for the TL effect started around 100 ms and lasted until 350 ms. However, the consecutive analysis of 50 ms time windows revealed no continuous TL priming effect, but a continuous repetition priming effect was found starting around 200 ms and lasting until 450 ms. The English group showed both TL and repetition priming effects. However, here, the TL condition showed a more negative-going wave compared to the control condition. In the CBPT only some small temporal clustering could be found for both effects starting around 150 ms for the repetition priming and around 50 ms for the TL priming effect. The consecutive analysis of 50 ms time windows revealed a sustained TL priming effect across almost the entire post-target period, while the repetition effect showed continuous activity from 350 to 600 ms.

The TF results are overall similar to those found for the longer prime duration; however, they seem to be more inconsistent than previously, especially for the theta and alpha bands, which might indicate differential demands on visual working memory between the two prime durations and/or less stable integration between prime and target at shorter prime durations. The activation differences in the beta band between German and English, however, seemed quite stable and showed consistently in power and ITPC even at short priming durations.

All in all, the findings of Experiment 2 on cross-modal TL priming replicated the TL priming effects of Experiment 1 in the unimodal paradigm in accordance with the hypotheses and in agreement with assumptions of the BIAM. These were apparent in the behavioral as well as in the neurophysiological data. The early effects observed way before a lexical level of processing indicate that cross-modal TL priming takes place at an early, sub-lexical level of processing. No language differences were found in the behavioral results, but ERP and TF results revealed important differences between German and English. Confirmatory ERP analyses showed TL priming effects in the N250 and the N400 time windows for both languages at prime durations of 66.67 ms. However, at shorter prime durations of 50.00 ms, no TL effect could be found for the German group, but the English group consistently showed a TL effect. This might indicate that the TL priming effect in the German group is limited to conscious processing but disappears at prime durations connected to subconscious perception and processing. The time-course of activation also showed sustained TL priming effects in the English group for both prime durations from the earliest epoch. In the German group, continuous TL priming effects could only be detected in later epochs. TF analyses revealed important processing differences in the beta band that were attributed to a differential involvement of grapheme-phoneme-mapping and orthographic-phonological integration between the two languages. Thus, despite similar effects in the behavioral data, the neurophysiological results indicate a stronger effect of TL priming in English compared to German in agreement with the assumptions and the previous findings.

3.4 Experiment 3

In Experiment 3, the goal was to replicate the findings of cross-modal TL priming effects found in Experiment 2 and to compare TL priming effects to a pseudohomophone (PsH) priming condition in order to disentangle orthographic and phonological contributions to cross-modal priming effects. Prime presentation was kept at a short interval of 50.00 ms to test TL and PsH priming at automatic, sub-lexical levels of processing.

3.4.1 Method

Participants. Thirty-two participants (22 female; mean age: 25.45 years) were recruited via the University's mailing list and randomly assigned to one of the two languages (German, English). All participants were right-handed German native speakers and reported no hearing impairments and had normal or corrected to normal vision. Participants reported a mean age of acquisition of English of 9.29 years (*SD* = 2.16, range = 4 to 12 years). LexTale scores were again collected from both groups and showed an average value of 79.94% with a standard deviation of 11.82% and a range of between 55% and 100%. This again corresponds to an upper intermediate to advanced level of English. Participants in the two language groups did not differ in age($t(28.837) < 1$, $p = .562$), age of acquisition ($t(28.775) < 1$, $p = .355$) or LexTale test score ($t(24.762) = 1.044$, $p = .307$).

Material. I used a subset of the targets of Experiment 1 and 2 and created pseudo-homophone (PsH) primes (e.g., Engl. *blowse – BLOUSE*, Ger. *bluhse – BLUSE*) by replacing either a vowel or a consonant with an equivalent phoneme. This resulted in an item set of 120 non-cognates, 120 cognates and 120 pseudo-words. Vowel and consonant replacement were balanced across the pairs of non-identical cognates, i.e., in 60 pairs, I replaced the vowel phoneme and in 60 pairs I replaced the consonant phoneme. I created three word lists and presented each target in each list with a different kind of prime (TL, PsH, control). This resulted in 40 items per participant per condition. The same control condition as in Experiments 1 and 2 was used for both TL and PsH primes. Stimuli were still matched in frequency ($t(445) < 1$, $p = .855$) as well as number of orthographic ($t(445) < 1$, $p = .953$) and phonological neighbors ($t(445) < 1$, $p = .335$) across languages. This was also true when computing the values separately for cognates (frequency: $t(235) < 1$, $p = .333$; orthographic neighbors: $t(235) < 1$, $p = .719$; phonological neighbors: $t(235) < 1$, $p = .376$) and non-cognates (frequency: $t(208) = 1.440$, $p = .155$; orthographic neighbors: $t(208) < 1$, $p = .743$; phonological neighbors: $t(208) < 1$, $p = .633$). The list of items can be seen in Table A3 of Appendix A.

Procedure. The procedure was identical to Experiment 2 except for the variation of prime duration. Prime duration was kept stable at 50.00 ms in this experiment.

Data pre-processing.

Behavioral data. Pre-processing of behavioral data was equal to Experiment 2. Reaction times lower than 350 ms and higher than 3,500 ms were excluded prior to further analysis. This concerned less than one percent of all data points. Prior to the analysis of reaction times, incorrect responses were excluded. This concerned 4.27% of all data points. Cook's distance was below 0.710 for all data points and consequently was lower than a cut-off threshold of D_i

< 1.000. However, some data points exceeded a cut-off threshold of $D_i < 4/n$. These data points were excluded prior to further analysis. This concerned 1.02% of all data points.

EEG data. EEG pre-processing was equal to Experiment 2. One participant of the English group was excluded from further analysis of the neurophysiological data due to a high level of noise and consequently a loss of more than 50% of the trials in at least one condition. After exclusion of this participant, on average 23.20% of all trials were rejected due to noise or incorrect answers. Individual rejection rates ranged from 0% to 50% of trials per condition. Thus, data sets were only analyzed further if at least 50% of trials in all conditions were retained after artifact rejection.

Data analysis. Data analysis for behavioral and neurophysiological data was equal to Experiment 2 without the factor of prime duration.

3.4.2 Results

3.4.2.1 Behavioral results. The logistic mixed effect model showed a main effect of language ($W(1) = 15.285$, $p < .001$, $R^2 = 0.092$). Neither the main effect of condition ($W(2) = 1.992$, $p = .369$) nor the interaction between condition and language ($W(2) = 1.413$, $p = .493$) reached significance. Accuracies were higher for the L1 German compared to the L2 English. The linear mixed effects model showed a significant main effect of condition ($W(2) = 8.545$, $p = .014$, $R^2 = 0.001$) and a marginally significant main effect of language ($W(1) = 3.052$, $p = .081$, $R^2 = 0.018$). None of the other effects reached significance. Reaction times were slightly lower for the L1 German than the L2 English. Post-hoc planned contrasts revealed a significant PsH priming effect ($z = 2.909$, $p = .007$, $d = 0.122$), but no effect of TL priming ($z = 1.668$, $p = .191$). Descriptive statistics can be seen in Table 18. Table 19 shows net TL and PsH effects.

Table 18

Descriptive statistics of accuracies and reaction times per condition and language for Experiment 3 on cross-modal TL priming

Condition	**Accuracy in %**	**Reaction times in ms**
TL	96.185	945.430 (180.478)
PsH	95.796	940.906 (171.779)
Control	95.215	952.782 (175.112)

Language	Accuracy in %	Reaction times in ms
German (L1)	98.499	925.105 (160.519)
English (L2)	93.116	967.805 (187.697)

Note. Accuracy refers to the percentage of correctly answered trials of all trials. Standard deviation in brackets.

3.4.2.2 ERP results.

Confirmatory analysis. The overall model showed a main effect of condition ($W(2) = 54.099$, $p < .001$, $R^2 = 6.209 \cdot 10^{-4}$), a main effect of ROI ($W(3) = 28.820$, $p < .001$, $R^2 = 3.154 \cdot 10^{-4}$) and a main effect of time window ($W(1) = 2232.337$, $p < .001$, $R^2 = 2.443 \cdot 10^{-2}$). The interactions between condition and language ($W(2) = 7.591$, $p = .023$, $R^2 = 1.843 \cdot 10^{-3}$) and between condition and time window ($W(2) = 16.781$, $p < .001$, $R^2 = 2.524 \cdot 10^{-2}$) also reached significance. The three-way interaction between condition, language and time window was marginally significant ($W(2) = 4.848$, $p = .089$, $R^2 = 2.754 \cdot 10^{-2}$). The four-way interaction did not reach significance. Subsequent analyses for the N250 time window showed a main effect of condition ($W(2) = 68.342$, $p < .001$, $R^2 = 1.532 \cdot 10^{-3}$) and a significant main effect of ROI ($W(3) = 69.059$, $p < .001$, $R^2 = 1.479 \cdot 10^{-3}$). None of the interactions involving condition reached significance. Planned contrasts showed significant differences between the TL and the control condition ($z = -4.851$, $p < .001$, $d = 0.062$) and between the PsH and the control condition ($z = -8.116$, $p < .001$, $d = 0.105$) irrespective of language. Both effects were in the opposite direction than expected, with the primed conditions showing more negative values than the control condition.

For the N400 time window, a main effect of condition ($W(2) = 6.225$, $p = .045$, $R^2 = 1.462 \cdot 10^{-4}$), a main effect of ROI ($W(3) = 8.253$, $p = .041$, $R^2 = 1.852 \cdot 10^{-4}$) and an interaction between condition and language ($W(2) = 8.808$, $p = .012$, $R^2 = 4.585 \cdot 10^{-4}$) could be observed. For the German group, a significant difference between the PsH and the control condition ($z = -2.791$, $p = .011$, $d = 0.048$), but not between the TL and the control condition ($z < 1$, $p = 1.000$) could be found. For the English group, a significant difference between the TL and the control condition ($z = -2.645$, $p = .016$) was found, but not between the PsH and the control condition ($z < 1$, $p = 1.000$). Grand average ERPs are plotted in Figure 16.

Table 19

Net TL and PsH priming effects per language of Experiment 3 on cross-modal TL priming

German					
	TL	**PsH**	**Control**	**ΔTL-Control**	**ΔPsH-Control**
Accuracy in %	98.831	98.833	97.833	0.998	1.000
RTs in ms	922.404	918.907	934.091	-11.687	-15.184

English					
	TL	**PsH**	**Control**	**ΔTL-Control**	**ΔPsH-Control**
Accuracy in %	93.681	92.936	92.733	0.948	0.203
RTs in ms	968.651	963.094	971.732	-3.081	-8.638

Cluster-based permutation test. For the German group, the permutation test showed significant spatial clustering for the electrodes F7, F3, Fz, F4, F8, FC1 and FC2 for the PsH condition compared to the control condition. Subsequent analysis revealed temporal clustering starting at around 200 ms and lasting about 50 ms. No other significant temporal clusters were found. For the TL condition no significant spatial or temporal clusters were found. For the English group, no spatial clusters were found for the PsH compared to the control condition. Investigation of single electrodes revealed significant temporal clusters starting around 180-200 ms at electrodes FC2 and P8. One early temporal cluster at around 50 ms was found at electrode O1. For the TL condition, no spatial clusters were found either. Temporal clustering was found around 250 ms and around 380 ms at electrodes Cz and O1. Here, too, one early cluster was found around 50 ms for electrode O1.

Analysis of successive 50 ms epochs. The overall model showed main effects of condition ($W(2) = 382.484$, $p < .001$, $R^2 = 4.141\cdot10^{-4}$) and of epoch ($W(11) = 20{,}760.878$, $p < .001$, $R^2 = 2.145\cdot10^{-2}$). The interactions between condition and epoch ($W(22) = 123.680$, $p < .001$, $R^2 = 2.199\cdot10^{-2}$), between condition and language ($W(2) = 118.036$, $p < .001$, $R^2 = 1.621\cdot10^{-3}$) and between condition, language and epoch ($W(22) = 191.402$, $p < .001$, $R^2 = 2.433\cdot10^{-2}$) also reached significance. Results for subsequent analyses by epochs are shown in Table 20.

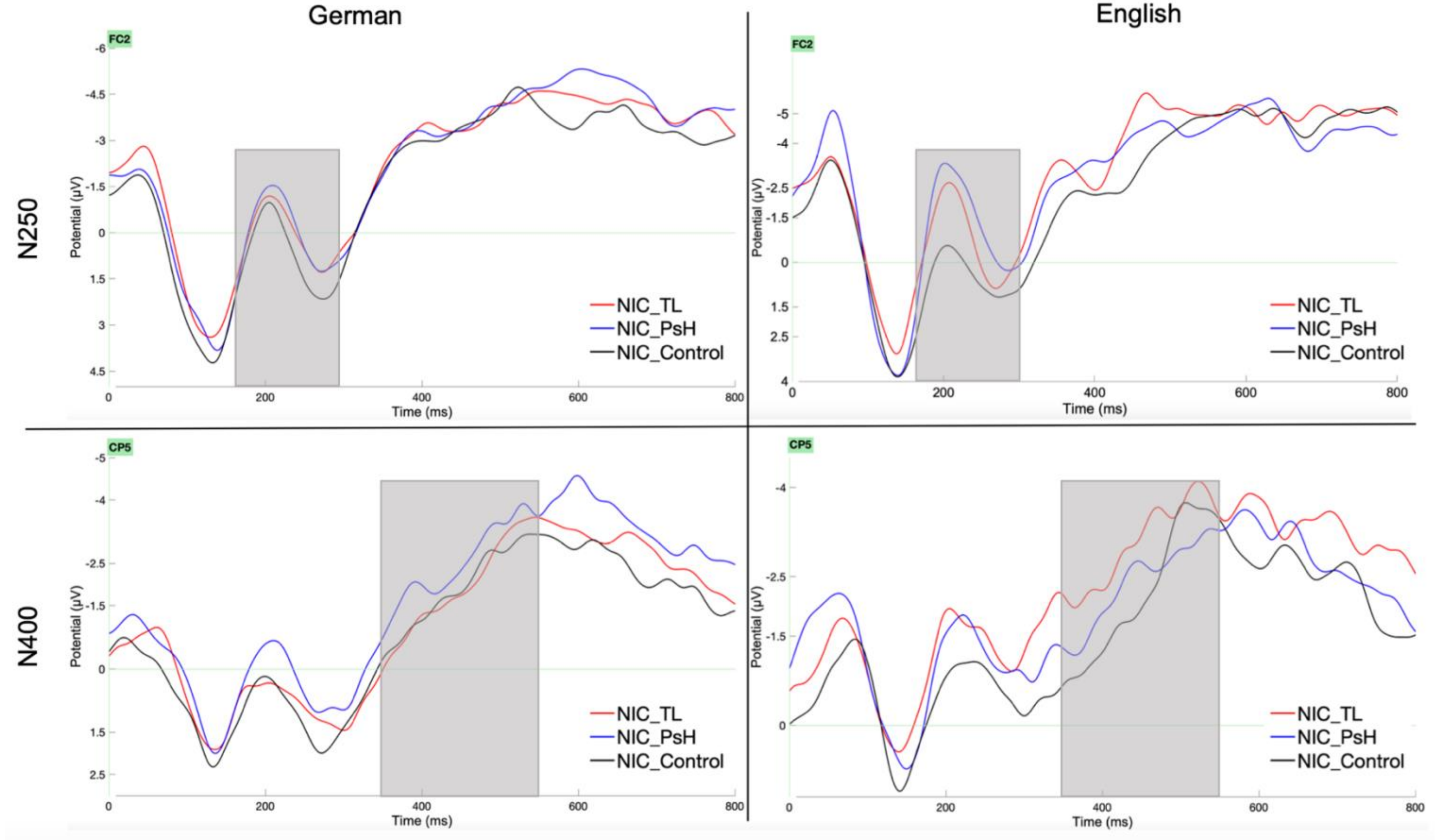
Table 20

Results of consecutive 50 ms epochs between 0 and 600 ms averaged over 30 electrodes for Experiment 3 on cross-modal TL priming

	TL priming effect		**PsH priming effect**	
Epoch (ms)	**German**	**English**	**German**	**English**
0-50	-	-	< .001	< .001
50-100	<.001	<.001	<.001	<.001
100-150	<.010	<.050	<.001	-
150-200	< .001	< .001	< .001	< .001
200-250	-	< .001	< .001	< .001
250-300	< .001	< .001	< .001	< .001
300-350	-	< .001	< .001	< .001
350-400	-	< .001	<.001	< .001
400-450	-	< .001	< .001	< .001
450-500	-	< .001	< .010	-
500-550	-	-	< .001	< .001
550-600	< .010	-	< .001	-

Figure 16

Grand-average ERPs of Experiment 3 on cross-modal TL priming



Note. Negativities are plotted upwards. NIC = non-identical cognate, TL = transposed letter condition, PsH = pseudohomophone condition. Grand-average ERPs were calculated group-wise for German (left) and English (right) as the target language. Time windows of interest are indicated in grey (N250: 150-300 ms; N400: 350-550 ms). The N250 component was visually maximal at fronto-central electrode sides (top), while the N400 effect showed a visual maximum at centro-parietal electrode sides (bottom). Please note that these differences were apparent visually but did not show in the statistical analysis. A 10 Hz filter was applied for visualization purposes.

3.4.2.3 TF results.

The following table gives an overview of all TF effects found for Experiment 3 on cross-modal transposed letter priming. A comprehensive description of all statistical results can be found in Appendix B.

Table 21

Overview of TF results of Experiment 3 on cross-modal TL priming

N250 time window					
Power					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
TL > control	delta	fronto-polar centro-parietal parietal	TL > control	delta	fronto-polar
Primed > control	delta	fronto-central	Primed < control	delta	centro-parietal parietal
PsH < control	theta	fronto-polar parietal	TL > control	theta	fronto-central
PsH < control TL > control	theta	fronto-central centro-parietal	Primed < control	theta	centro-parietal parietal
Primed < control	alpha	fronto-polar centro-parietal parietal	TL > control	alpha	fronto-central centro-parietal parietal
PsH < control	alpha	fronto-central			
PsH < control TL > control	beta	fronto-polar fronto-central	Primed < control	beta	fronto-polar fronto-central
Primed < control	beta	centro-parietal	Primed < control	beta	centro-parietal
PsH < control	beta	parietal	PsH < control	beta	parietal
Primed < control	gamma	fronto-polar fronto-central centro-parietal	Primed > control	gamma	fronto-polar fronto-central centro-parietal parietal
TL < control	gamma	parietal			
ITPC					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
			PsH > control	delta	fronto-polar
Primed < control	theta	fronto-central centro-parietal parietal	PsH > control	theta	fronto-polar fronto-central
			TL > control	theta	parietal
TL < control	alpha	fronto-polar fronto-central	PsH > control	alpha	fronto-polar
Primed < control	alpha	centro-parietal parietal	TL < control	alpha	parietal

PsH < control	beta	fronto-polar	TL < control	beta	fronto-polar fronto-central
TL > control	beta	fronto-central			
PsH < control TL > control	beta	centro-parietal parietal	PsH < control TL > control	beta	centro-parietal parietal
Primed > control	gamma	fronto-polar	Primed < control	gamma	fronto-polar fronto-central centro-parietal
PsH > control TL < control	gamma	fronto-central	TL < control	gamma	parietal
PsH > control	gamma	centro-parietal parietal			
N400 time window					
Power					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Primed > control	delta	fronto-polar fronto-central centro-parietal parietal	TL > control	delta	fronto-polar fronto-central
			PsH < control	delta	centro-parietal
			Primed < control	delta	parietal
PsH > control	theta	fronto-polar	TL > control	theta	fronto-polar fronto-central
TL > control	theta	fronto-central centro-parietal	PsH < control TL > control	theta	centro-parietal
PsH < control TL > control	theta	parietal	PsH < control	theta	parietal
PsH > control	alpha	fronto-polar	PsH < control	alpha	fronto-central
TL > control	alpha	fronto-central	TL > control	alpha	parietal
PsH < control TL > control	alpha	centro-parietal	PsH < control TL > control	alpha	centro-parietal
PsH < control	alpha	parietal			
Primed < control	beta	fronto-polar fronto-central	Primed > control	beta	fronto-polar
TL < control	beta	centro-parietal	TL > control	beta	fronto-central
			PsH < control	beta	centro-parietal parietal
Primed < control	gamma	fronto-polar fronto-central	Primed > control	gamma	fronto-polar fronto-central centro-parietal
PsH < control	gamma	centro-parietal			
TL > control	gamma	parietal			
ITPC					
German			**English**		
Effect	**Band**	**ROI**	**Effect**	**Band**	**ROI**
Primed < control	delta	fronto-polar fronto-central			

		centro-parietal parietal			
Primed < control	theta	fronto-polar fronto-central parietal	Primed < control	theta	fronto-polar fronto-central
TL < control	theta	centro-parietal			
Primed < control	alpha	fronto-polar fronto-central parietal	TL > control	alpha	fronto-polar fronto-central centro-parietal
Primed > control	alpha	centro-parietal	Primed < control	alpha	parietal
Primed < control	beta	fronto-polar fronto-central	TL > control PsH < control	beta	fronto-polar
TL < control	beta	parietal	TL > control	beta	fronto-central
Primed > control	beta	centro-parietal	Primed > control	beta	centro-parietal parietal
Primed > control	gamma	fronto-polar	PsH < control	gamma	fronto-central
Primed < control	gamma	fronto-central centro-parietal	PsH > control	gamma	centro-parietal
PsH < control	gamma	parietal	PsH > control TL < control	gamma	parietal

Note. TL = transposed letter prime, PsH = pseudohomophone prime.

3.4.3 Summary

Experiment 3 was conducted to replicate findings of cross-modal TL priming found in Experiment 2 and to compare the orthographic TL priming effects with phonological PsH priming effects. The prime duration was kept at 50.00 ms to investigate whether cross-modal TL and PsH priming effects can be found at prime intervals connected to automatic, subconscious processing. The behavioral data showed a significant PsH priming effect apparent as reduced reaction times for both languages. However, the TL priming effect was not significant in either of the two groups. Accuracies did not reveal an effect of priming at all. However, accuracy values were very high with above 90% correct responses regardless of language and condition, which indicates ceiling effects and explains the lack of findings. Descriptively, the TL priming condition showed lower reaction times compared to the control condition, however, this difference did not reach significance. This might be due to power issues. No language differences were found in the behavioral data.

ERP results showed significant TL and PsH priming effects for the German and the English group in the N250 time window. In the N400 time window, the German group showed significant PsH priming, while in the English group, only the TL condition was significantly different from the control condition. All effects showed the opposite direction than expected, with the primed conditions displaying more negative-going wave forms than the control condition. These findings were confirmed by the CBPT and the time-course analysis. CBPT revealed a broad spatial cluster for the PsH condition with temporal clusters starting at around 200 ms for the German group, but no clusters could be identified for the TL condition. For the English group, no spatial clusters could be found for either condition. However, temporal clusters revealed an onset of PsH priming effects of around 200 ms as well and an onset of around 250 ms for the TL priming effect with early clusters showing at around 50 ms. The consecutive 50 ms analysis showed a sustained TL priming effect for the English group starting at 50 ms and lasting until 500 ms. For the German group, the TL effect was less continuous and lasted only until 300 ms. For the PsH effect, the opposite pattern was found: This effect was more stable and pronounced for the German group, starting at the earliest epoch and lasting until 600 ms. For the English group, the effect was less continuous, which might explain a failure to detect the effect in the N400 time window.

As for the shorter prime duration of Experiment 2, TF effects were quite inconsistent in the delta, theta, alpha and gamma bands with ambiguous and at times contradictory results especially when taking both power and ITPC into account. This might indicate less stable effects for lower prime durations compared to the longer prime duration of 66.67 ms. The previously observed differences in the beta band remained and were especially pronounced for the TL condition in the N400 time window. Beta desynchronization was observed for German for both prime conditions, while higher power and ITPC were observed for the TL condition in English. The PsH condition exhibited the same effects in both languages. This is in line with the assumption that the observed processing differences in the beta band might be connected to the modulation of brain regions involved in orthographic processing as a function of orthographic depth. However, in the N250 time window, differences in beta band activity between the two languages were less consistent.

In sum, these findings replicate the results of Experiment 2 and indicate cross-modal TL priming effects in late German-English bilinguals in their L1 and their L2. Contrary to Experiment 2, the TL priming effect was also present for the German group at a short priming duration of 50.00 ms which suggests an automatic effect of TL priming on spoken word processing. However, this effect might not be as stable in the German group and might be dependent on the sample. This is corroborated by a failure to detect a TL priming effect in the N400 time window, while the PsH effect persisted over the entire post-stimulus period. The English group showed the exact opposite pattern with a sustained TL priming effect in both time windows, while the PsH effect was limited to the N250 time window and was less continuous than for the German group. This might indicate a stronger importance for phonological information in spoken word recognition in German, but for orthographic processing in English.

3.5 Discussion

The aim of this study was to investigate bimodal processing of orthography and phonology as a function of orthographic depth in a paradigm that allows for a tight control of cross-linguistic stimulus material and to replicate the findings of study 1. The TL priming paradigm was used, a research design well established in the investigation of orthographic priming in visual word recognition. Non-identical cognate words were chosen as the critical stimulus material and manipulations within item pairs were tightly controlled across the two languages to achieve maximum comparability of the cross-linguistic stimulus material while controlling for relevant factors. For the first time, I used a cross-modal design with a visual prime and an auditory target to prompt bimodal processing in accordance with assumptions of the BIAM. Though TL priming effects have previously been argued to rely solely on orthographic representations and are said not to be phonological in nature (e.g., Eddy et al., 2016; Grainger et al., 2006; Kinoshita & Norris, 2009; Meade et al., 2020; Perea & Carreiras, 2006, 2008), the BIAM suggests bimodal processing of words irrespective of the input modality. Following this assumption, I proposed that it should be possible to use a visual TL prime to pre-activate an auditory target word. In agreement with the findings of study 1, I hypothesized that cross-modal TL priming should affect shallow orthographies less than deep orthographies.

In a first experiment, I investigated TL priming in late German-English bilinguals in a unimodal (visual prime – visual target) paradigm and found significant TL priming effects in both German and English apparent as reduced reaction times for the primed conditions relative to an orthographic control condition in agreement with previous findings. In the second experiment, I used the same stimulus material in a cross-modal (visual prime – auditory target) design with behavioral and neurophysiological methods and found significant TL priming effects in both languages. The pattern of the behavioral data was very similar to that found in the unimodal design with reduced reaction times for targets following repetition and TL primes compared to an orthographic control condition. ERP data confirmed these results and showed significant TL priming in the N250 and the N400 time window for both languages with reduced amplitudes for the TL condition compared to the orthographic control condition for priming durations of 66.67 ms. The repetition priming condition was only significant in the N400 time window for both languages, indicating that TL priming takes place at an earlier level of processing than repetition priming. The time course of activation showed an early sustained TL priming effect for the English group starting at the earliest epoch and lasting until 350 ms. For the German group, the TL priming condition only showed a continuous effect from 250 ms onwards. At a shorter prime duration, a continuous TL priming effect was no longer present for the German group, but the English group still exhibited an early sustained effect of TL priming. The repetition priming effect was still significant for both groups. Experiment 3 contrasted the TL condition with a PsH condition at a prime duration of 50.00 ms. Here, TL priming effects could be elicited for the German group in the N250 time window but were no longer present in the N400 time window. For the English group, TL effects were again early and long-lasting, affecting processing in both confirmatory time windows and showing a sustained effect from 50 ms until 500 ms. The PsH effect showed significant priming in the N250 time window for both groups but was no longer present in the N400 time window for the English group.

Taken together these findings are in agreement with my assumptions and the findings of study 1 and are evidence for bimodal word processing in deep and in shallow orthographies. The results also show a stronger effect of cross-modal TL priming for deep orthographies, apparent in earlier, longer lasting, and more reliable TL priming effects in English compared to

German. Results of Experiment 3 specifically indicate a double dissociation with inverted effects of TL and PsH priming in English and German: While both priming effects were significant in the N250 time window in both languages, TL effects lasted in English while PsH effect remained significant in German until the N400 time window associated with lexical access. This might indicate a stronger reliance on orthographic representations in English, but phonological representations in German. Considering the higher number of homophones in English, relying only on phonological representations is not feasible to access the correct lexical entry of a word form due to a high amount of ambiguity. A stronger dependence on orthographic information during spoken word processing might be advantageous in deep orthographies to preferentially activate the most likely candidate. Contrarily, in a shallow orthography such as German, phonology is given priority in spoken word processing, because it exhibits less ambiguity and is, therefore, reliable. Depending on orthographic information is not necessary to access the correct lexical entry.

The significant modulation of the N250 amplitude as well as the time-course of activation reveal an early effect of TL priming on spoken word processing well before latencies connected to lexical access for both shallow and deep orthographies. This contradicts the extension of the BIAM proposed by Grainger and Ziegler (2011). Based on their extension of the model, it was assumed that activation of phonology by visually presented TL primes occurs at the level of whole word units. The authors propose a coarse-grained and a fine-grained route of orthographic processing. The coarse-grained route uses a "good enough" approach and relies on orthographic representations that only code relevant information for a fast access to lexical-semantic representations such as word length, informative letter combinations, first and last letter of a word, etc. Most importantly, this route does not code the exact position of letters within a word. TL priming is said to take place via this route while pseudohomophone priming is only possible via the fine-grained route that codes letter order in detail. While the fine-grained route is connected to sub-lexical phonology, the coarse-grained route is not. Consequently, I assumed that the involvement of phonology in TL priming takes place at the whole-word level. However, TL priming and PsH priming in this study showed almost identical onset times, which indicates that they take place at the same, early level of processing. Thus, it needs to be assumed that TL primes are connected to sub-lexical phonology as well.

Regarding the time-course of activation, it should be kept in mind, however, that the baseline correction was discontinuous for this study. The presentation of the fixation cross was chosen as the baseline, because it was deemed the cleanest part of the trial. Baseline correction is applied to correct for skin potentials that affect the offset and the form of the ERP component in the post-stimulus time window. For ERP studies, a baseline of 100 to 200 ms directly preceding target onset is usually chosen. The activity in this pre-stimulus window is subtracted from every time point in the analyzed epoch, thereby correcting the electrophysiological signal in the post-stimulus time window for non-stimulus related activity. This also means that the pre-stimulus period is averaged to zero and the voltage amplitude of ERP components at 0 ms is on average 0 µV (Luck, 2014). However, if the baseline is discontinuous, the period directly preceding target presentation is not averaged to zero and differences due to stimulus-related activity following prime presentation could be present in the pre-target epoch. Therefore, the activity measured at time point 0 ms will not be 0 µV and might differ between conditions even before presentation of the target. This might explain the very early findings in an epoch of 0 to 50 ms. Hence, the very early onset of effects should not be overinterpreted. However, the confirmatory analysis also revealed effects at latencies connected to sub-lexical processing (Grainger et al., 2006).

TF results were less consistent in this paradigm than in the auditory priming paradigm of study 1 and showed some striking differences to the previous study. Alpha and theta synchronization was observed for primed conditions relative to the unprimed condition in the current studies, while the opposite pattern was found for study 1. The increase in neuronal activity for the theta and alpha band was present for both languages and was attributed to visual working memory load and the integration of the prime retrieved from short-term working memory and the encountered target word. A striking pattern was found for the beta band: Beta band activity was reduced for German but enhanced for English specifically for the TL condition. In reference to findings by Klimesch et al. (2001), this was attributed to differences in activation of the left IFG and the angular gyrus involved in grapheme-phoneme conversion and orthographic-phonological integration, respectively. As discussed in the General Introduction, activity in the left IFG is modulated by the orthographic depth of the target language and is increased in orthographic processing in deep orthographies relative to shallow orthographies (e.g., Booth et al., 2004; Cherodath & Singh, 2015; Paulesu et al., 2000). The current findings are in line with these assumptions and additionally indicate a differential involvement of the angular gyrus in bimodal processing in languages with different orthographic depths.

The direction of priming effects was also less predictable in this paradigm. In Experiments 2 and 3, both facilitative and inhibitory priming effects were found. While TL priming effects were facilitative for both languages at a prime duration of 66.67 ms, TL and PsH effects were inhibitory at a prime duration of 50.00 ms. The repetition priming effect was facilitative for German irrespective of prime duration. For English, this effect was inhibitory at a prime duration of 66.67 ms, but facilitative at 50.00 ms. Inhibitory priming effects are particularly surprising in these studies because neither TL nor PsH or repetition primes are known to exhibit inhibition. In repetition priming, the target accesses the same entry in the mental lexicon as the prime, therefore, target processing should be facilitated. TL and PsH primes are pseudowords and have no entry in the mental lexicon because they are non-existent. Prime lexicality is usually the factor that drives facilitation versus inhibition in masked priming paradigms: Word primes usually produce inhibition, while pseudoword primes produce facilitation when prime and target are orthographically or phonologically related (e.g., Davis & Lupker, 2006; Ferrand & Grainger, 1996; Kida et al., 2022). For the TL paradigm, word primes (e.g., *trial – trail*, *casual–causal*) have been found to lead to null effects rather than inhibition (Duñabeita et al., 2009). The inhibitory effects of word primes are driven by lexical competition between entries in the mental lexicon contending for activation. When a word is activated in the mental lexicon it will inhibit its orthographic and phonological neighbors to ensure access to only the word that is currently relevant for language comprehension. The inhibitory effect found for O+P+ primes in study 1 was attributed to lateral lexical inhibition. However, this is not plausible in this study because pseudowords do not have an entry in the mental lexicon and can, therefore, not exhibit lexical inhibition. Inhibitory priming effects have been observed in cross-modal transposed-phoneme priming (Dufour et al., 2022). However, the authors also used existing words as primes and attribute their findings to lexical competition.

Consequently, it seems difficult to draw strong conclusions from the direction of the observed effects. This is additionally complicated by the lack of a native English control group. Hence, it is not possible to know whether the effects are specific to native German speakers and stem from the German system or are general effects that are not language specific but might be caused by the paradigm. The fact that the TL effect was facilitative in nature in both groups for longer prime durations suggests that the prime interval might play a role in the direction of effects. Prime duration in masked priming paradigms has previously been found to influence the direction of priming effects in visual word recognition. However, usually, the opposite pattern is observed: Effects are reported to be inhibitory at longer priming durations, while inhibition is reduced or canceled out at shorter prime intervals (e.g., New & Nazzi, 2012; Robert & Mathey, 2011). In the current experiments, facilitation was observed at longer and inhibition at shorter prime intervals. Moreover, the inhibitory effects were only present in the ERP data. Behaviorally, reduced reaction times and, thus, facilitative effects of TL and PsH priming were found.

However, just as discussed for study 1, the behavioral data of the current experiments need to be interpreted with care due to power issues. Though, the number of trials per condition were increased in the experiments of study 2 with 50 or 40 trials, only 15 participants per subgroup were tested. This results in 750 or 600 observations per condition, which is again well below the 1,600 observations suggested by Brysbaert and Stevens (2018). Moreover, power was calculated based on the method suggested by Kumle et al. (2021) using a standardized beta coefficient of 0.100 as the smallest effect size of interest. This corresponds to a small effect size (Nieminen, 2022). While power for the repetition condition was adequate in both paradigms, data-based values indeed indicate power issues for the detection of the TL and the PsH priming effects. Power for these conditions was well below 80% in all experiments with a maximum of around 50% power. Hence, sample sizes for the TL and PsH priming paradigm should be increased in the future to replicate the behavioral findings with adequately powered studies.

4. General Discussion and conclusion

This thesis was guided by two research questions: Can the evidence for a bimodal processing of spoken words consistently reported for deep orthographies such as English and French be generalized to a shallow orthography such as German? And do bilinguals with representations of languages with different orthographic depths transfer effects of their L1 to their L2 or do they flexibly adapt bimodal processing mechanisms to the target language? Previous research suggests a crucial role of orthographic depth in the processing of orthographic information (e.g., Goswami, 2010; Landerl et al., 1997; Rau et al., 2015; Schmalz et al., 2015; Seymour et al., 2003; Wimmer & Goswami, 1994). Reading-related behavior substantially varies across languages as a function of orthographic depth. This is reflected in theoretical accounts proposing different representational structures of orthography and phonology (Katz & Frost, 1992; Ziegler & Goswami, 2005) as well as in the differential patterns of neuronal activation found in brain areas related to orthographic and phonological processing for deep versus shallow orthographies (e.g., Cherodath & Singh, 2015; Fiebach et al., 2002, Paulesu et al., 2000). Brain activation patterns also suggest that bilinguals flexibly adapt processing mechanisms in visual word recognition to the target language (Buetler et al., 2014). Based on these findings, I hypothesized that orthographic depth should affect the influence of orthography on spoken word processing and that bilinguals should adapt bimodal processing mechanisms to the orthographic depth of the target language.

4.1 Orthographic depth modulates bimodal word processing

The studies reported in this thesis consistently found that orthographic depth modulates the on-line processing of orthographic information during spoken word recognition. The ERP results of study 1 showed inhibitory effects of orthographic overlap in auditory priming for late German-English bilinguals in German but facilitating effects in English. The latter findings were a direct replication of a previous experiment conducted with English native speakers who also exhibited facilitating effects of orthographic overlap in auditory processing (Perre et al., 2009). The differences were apparent in a time window of 400 to 500 ms and were accompanied by theta band increases for the orthographic overlap condition relative to a priming condition with no orthographic overlap in German. In English, theta band activity was lower for orthographic overlap compared to conditions showing no orthographic similarities between prime and target. Consequently, the processing differences were attributed to lexical lateral inhibition of orthographic neighbors in spoken word recognition in German. Similar findings have already been reported in visual word recognition where inhibition of orthographic neighbors was found for shallow orthographies, but facilitating effects were found for English (e.g., Carreiras et al., 1997; Grainger, 1990; Grainger & Segui, 1990; Sears et al., 1995, 2006; Siakaluk et al., 2002; van Heuven et al., 1998). This is evidence that the orthographic depth of a language modulates the orthographic neighborhood structure and influences neighborhood effects in both visual and spoken word recognition. The neighborhood structure is language-specific even in late bilinguals, which shows that processing mechanisms are not transferred from the L1 to the L2 but are flexibly adapted to the currently activated language at least in proficient speakers.

The results of study 2 confirmed these findings by revealing cross-modal TL priming effects in late German-English bilinguals in both German and English. The strength of the TL priming effect was modulated by the orthographic depth of the target language with earlier, more sustained, and more stable TL priming effects in English than in German. Results on TL and PsH priming effects revealed a double dissociation between the two languages with inverted effects: In a time window of 350 to 500 ms associated with lexical processing, TL effects were observed for English, but PsH effects were found for German. This indicates a stronger reliance on orthographic information in spoken word recognition for English due to a higher number of homophones in deep orthographies. In German, phonological information is prevalent in auditory target processing because it is more reliable in shallow orthographies. This is supported by dissociations in beta band activity. Beta band desynchronization was found for TL priming in German, but synchronization was found in English. These differences in beta band activation were located at electrode positions associated with activity in the left IFG and angular gyrus and indicate a differential involvement of these regions in orthographic processing during spoken word recognition as a function of orthographic depth (Klimesch et al., 2001). Activation patterns of TL effects revealed early, sub-lexical influences of orthography in spoken word recognition in agreement with previous findings (e.g., Pattamadilok et al., 2010; Perre & Ziegler, 2008; Salverda & Tanenhaus, 2010). These effects were also present in a masked priming paradigm with brief presentations of the prime. In agreement with insights gained from masked pseudohomophone priming in visual word recognition (e.g., Frost, 1998; Rastle & Brysbaert, 2006), these findings illustrate a fast and automatic activation of orthographic information during spoken word recognition.

Notably, language differences were limited to neurophysiological data. Even though the behavioral data in these studies has diminished interpretational value due to a lack of power caused by small sample sizes, descriptive statistics for reaction times and accuracies reveal similar behavioral patterns irrespective of the orthographic depth of the target language. The differential activation pattern of the electrophysiological data did not translate to behavior. Specifically, the lateral lexical inhibition found for orthographic overlap in German in study 1 showed no inhibition of responses in the lexical decision of the auditory target. Rather, reaction times were lower for targets preceded by orthographically related primes compared to conditions without orthographic overlap. This indicates that neural inhibition might be task-relevant and inhibition of orthographic neighbors during spoken word recognition might be necessary to achieve successful lexical access in shallow orthographies. Stronger reductions in reaction times were found for TL priming in German compared to English, while ERP and TF results indicated more sustained effects in English. This provides evidence that orthographic depth affects the on-line processing of bimodal information but influences response times and accuracies in lexical decision to a lesser degree. Therefore, neuroscientific methods are necessary to identify cross-linguistic differences in bimodal spoken word processing and to fully grasp the underlying cognitive-linguistic mechanisms.

The findings of this thesis reveal an important issue for psycho- and neurolinguistic research: Conclusions are often drawn based on findings in single languages and oftentimes this language is English. This means that evidence in psycho- and neurolinguistics is highly biased by characteristics of the English language system and findings, even if highly replicable across experiments, might not generalize to other languages. This is particularly relevant for research of orthographic processing because, as has been established in the General Introduction, the English orthography is not prototypical for alphabetic languages but is an outlier. English has an exceptionally deep orthographic system that is both highly complex and highly inconsistent. As such, it is not representative for other orthographic systems. This has important consequences for the assumed connections between orthography and phonology and, as mentioned above, among other aspects influences neighborhood structures, which leads to different effects in English relative to other languages. This has relevant implications for existing models of bimodal word processing.

4.2 Implications for current models of bimodal processing

It has been argued that the findings reported in this thesis are generally in agreement with the BIAM. The BIAM assumes bidirectional connections between orthography and phonology at sub-lexical and lexical levels of processing irrespective of the input modality. Therefore, it can explain the influence of orthography on spoken word recognition. Auditory features activate sub-lexical phonological units (phonemes) which feed activation forward in two directions: To sub-lexical orthographic units (graphemes) and to whole-word phonological units. The activated graphemes in turn activate their connected whole-word orthographic units. Whole-word units of both modalities are connected to each other and to the respective semantic units. Interactive activation models support within- and between-level excitatory and inhibitory connections. Therefore, the differential activation patterns observed for German and English can in principle both be modeled within the framework of the BIAM. However, because the BIAM in its current version is based on English, the nature and weights of the connections would need to be adapted to the orthographic depth of the language. For example, study 2 showed stronger effects of TL priming for English than for German. This might indicate that connections between orthographic and phonological representations are weaker for German than for English and orthographic information is given less weight in spoken word processing in shallow orthographies.

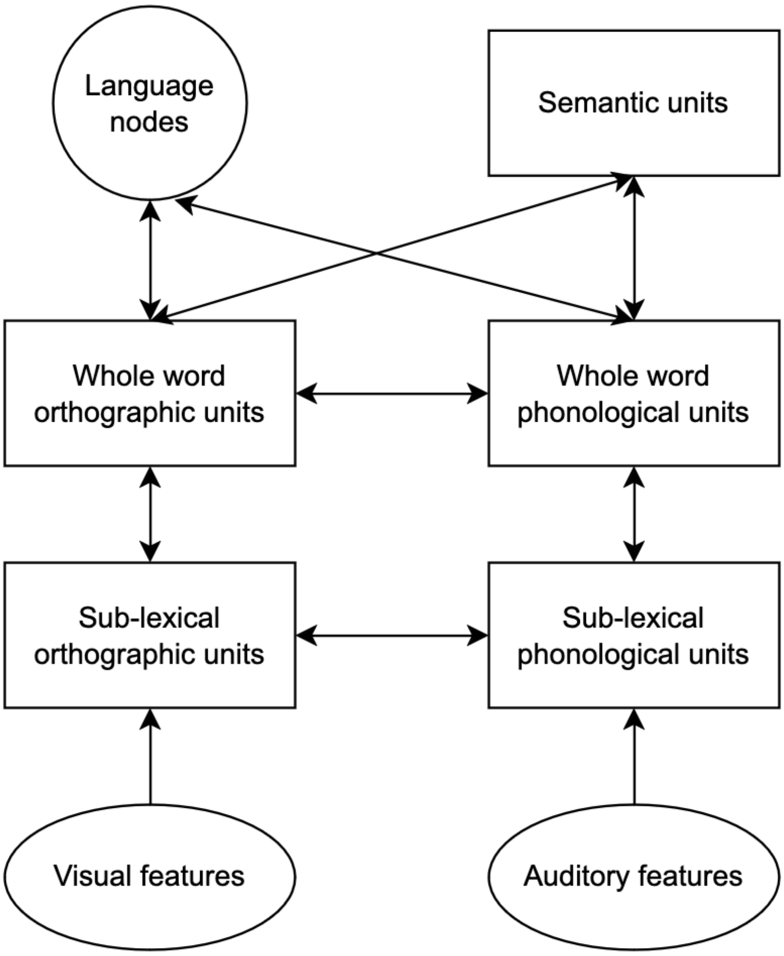
The BIAM has been extended by Grainger and Ziegler (2011) to explain TL and PsH priming effects. The authors propose two different kinds of sub-lexical orthographic units: One type of units is based on coarse-grained information involving only the most informative letter combinations of a word irrespective of letter order, while the other is based on fine-grained information that codes the exact letter positions in a word. Fine-grained sub-lexical orthographic units, but not coarse-grained units, are connected to sub-lexical phonological units because the order of phonemes needs to be observed to enable successful processing of phonological information. This extension of the BIAM is suitable to explain TL priming effects via the coarse-grained route while still maintaining the ability to differentiate between words like *trial* and *trail* or *casual* and *causal* via the fine-grained route. However, the lack of a connection between coarse-grained route and sub-lexical phonological units cannot be upheld in the face of current evidence. Cross-modal TL priming effects of study 2 were as early as PsH priming effects, revealing that a visual TL prime activates phonological information at a pre-lexical level of processing. Thus, the connections between orthographic and phonological units in the coarse-grained route cannot be limited to the whole-word level as suggested by Grainger and Ziegler (2011). Rather, the coarse-grained orthographic representations need to include connections to sub-lexical phonological units in a similar way as proposed for PsH priming.

The BIAM as well as its extension proposed by Grainger and Ziegler (2011) model bimodal word processing in a single language. However, there is an extension of the BIAM for bilingual processing: The Bilingual Interactive Activation Model (BIA+; Dijkstra & van Heuven, 1998, 2002). The core assumption of the BIA+ is language non-selectivity in an integrated lexicon. This means that whenever a stimulus is presented, matching orthographic and phonological representations are activated regardless of the language they belong to. This is specifically relevant to explain cross-linguistic priming effects in bilinguals indicating that bilingual word recognition is affected by orthographic, phonological, and semantic overlap between languages (Dijkstra & van Heuven, 2002). Rather than assuming separate mental lexica for different languages (language selective access), the suggestion of an integrated lexicon is better able to explain empirical findings on bilingual word recognition. The basic architecture of the BIA+ is identical to the BIAM as can be seen in Figure 17. Bidirectional connections between sub-lexical and lexical orthographic and phonological units are assumed in the model. The whole-word orthographic and phonological units are connected to the respective semantic representations. The crucial difference lies in the assumption of language nodes. These language nodes are proposed to be "language membership representations" (Dijkstra & van Heuven, 2002, p. 186) that signal which language a specific lexical unit belongs to. A language node is activated by whole-word orthographic or phonological representations of its language. The language nodes in turn excite words consistent with them and inhibit words that do not correspond to them.

Importantly, language nodes that allow the affiliation of a word to a specific language are assumed to be post-lexical. Hence, sub-lexical differences in bimodal processing between languages are not supported by the BIA+. Cross-linguistic differences in neighborhood effects are explained by top-down modulation of the language nodes. In a series of progressive demasking and lexical decision experiments with Dutch-English bilinguals, van Heuven, Dijkstra and Grainger (1998) demonstrated that an increase in target neighborhood size leads to inhibition effects in Dutch visual word recognition and facilitation effects in English visual word recognition. They argue that this is in line with the assumptions of the BIA+ model and explain these differences in terms of word frequency in combination with asymmetric top-down inhibition from the language nodes. Thus, language-specific differences are restricted to post-lexical processing. However, the findings of study 2 provide evidence for a pre-lexical locus of bimodal processing differences. A modulation of the TL priming effect in study 2 could be observed at latencies way before lexical access. TL effects in English occurred earlier and were more sustained in epochs of latencies corresponding to the N250 component that is associated with sub-lexical processing. This indicates that connections between sub-lexical orthography and sub-lexical phonology are modulated by orthographic depth and are, thus, language specific.

Figure 17

Architecture of the BIA+ model



Note. Adapted from Dijkstra & van Heuven (2002).

Differences in orthographic neighborhood effects between German and English as revealed by study 1 suggest that lateral connections at the lexical level are affected by orthographic depth, while the results of study 2 are evidence for a modulation of within-level connections at the sub-lexical stage. Therefore, language-specific differences in these connections need to be considered in the model in order to explain the current findings. The assumption of post-lexical language nodes as the only language-specific representations in the mental lexicon cannot be upheld. To model the complex language-specific interactions between orthography and phonology, connectionist approaches could be helpful and can be used for model revisions and future models of bilingual and multilingual processing. Connections between linguistic representations are without a doubt highly complex and can most likely not be adequately depicted and modeled without assuming an extensive network of excitatory and inhibitory connections between units that might be language specific and receive different weights for different languages. Connectionist models are not only suitable to reflect the intrinsic mechanisms of the human brain, but also allow to mathematically model and simulate activation patterns for different languages, thereby enhancing our understanding for the complex mechanisms of the bilingual brain.

4.3 Limitations and directions for future research

The studies described in this thesis were the first to systematically compare two languages of different orthographic depths with regards to processing differences and cognitive mechanisms involved in bimodal spoken word recognition using neuroscientific methods and have brought to light important new insights. However, German and English, the languages compared in the current studies, differ in both complexity and consistency. German is considered consistent and simple, while English is considered inconsistent and complex. Thus, the observed differences in the on-line processing of orthographic information during spoken word recognition could be caused by either of the two components or by their combination. By only contrasting German and English it is impossible to know which factor drives the differential activation patterns. In the General Introduction, I have established that the French orthography provides an interesting case, because it is located at different ends of the complexity-consistency-continuum: Grapheme-phoneme-correspondences in French are extremely complex, but highly consistent. Thus, I suggest that further research should use French as a connecting link to solve this issue. A comparison between German (simple, consistent) and French (complex, consistent) can isolate the effect of complexity on the bimodal processing of spoken words and the comparison between English (complex, inconsistent) and

French (complex, consistent) can isolate the effect of consistency (see also Schmalz et al., 2015). The comparison between German and English provided here then illustrates the effect of a combination of the two factors. Thus, a full picture on the influence of orthographic depth on the bimodal processing of spoken words emerges.

Processing differences between German and English were not only apparent in ERP components, but also in the TF measures. These measures provided additional information on the cognitive mechanisms underlying the observed differences in the ERP. However, the interpretational value of TF measures in this thesis is diminished by both methodical and theoretical reasons. TF measures, especially ITPC, were affected by the small number of trials that remained after artifact rejection. This was due to long epochs that were chosen to include a clean baseline. This was specifically challenging in the auditory priming paradigm because the period of interest is preceded by the prime. The paradigms used in these studies were not designed with the goal of computing TF measures, which complicated and restricted the analyses. TF measures are valuable additions in EEG analysis to identify relevant cognitive mechanisms and enhance the interpretational value of neurophysiological data. In the future, experimental designs more suitable for TF analyses should be established and used to achieve better results and a more profound understanding of the cognitive mechanisms underlying processing differences.

Moreover, TF analyses in the reported studies were exploratory in nature. The aim of exploratory analyses is not to test hypotheses, but to generate new ones in order to gain new insights in the field of research. Thus, the interpretations I proposed based on the TF analyses should not be confounded with the conclusions based on the confirmatory, hypotheses-driven analyses. Rather, these observations should be taken as starting points for new investigations that are suited to test the observations in a confirmatory manner by limiting analyses to specific frequency bands. These analyses will only gain more importance in the future to establish TF measures in the field of language processing. Currently, evidence on all language-related functions, but specifically for orthographic processing, is currently lacking. It is still largely unknown how activity in different frequency bands relates to the processing of different linguistic information and to behavioral output.

4.4 Conclusion

This thesis has provided reliable evidence that the processing of spoken words is bimodal in shallow and in deep orthographies, but the nature and extent of orthographic influences on spoken word recognition is modulated by the orthographic depth of the target language. This is in line with the existing literature on bimodal word processing and confirms assumptions of the Bimodal Interactive Activation Model. The proficient late German-English bilinguals investigated in these studies have been found to flexibly adapt bimodal processing mechanisms to characteristics of the target orthographic system in accordance with findings of visual word processing. Influences of orthographic depth on target language processing occurred early at a sub-lexical level. This contradicts the assumption of a language non-selective integrated lexicon as proposed by the Bilingual Interactive Activation Model. Rather, language-specific connections between orthography and phonology at sub-lexical and lexical levels of processing need to be assumed. This thesis and its results should encourage neuroscientific research of orthographic and phonological interactions in languages other than English and German to replicate and extend the current findings to a divers set of languages.

Supplementary material

Supplementary material for this thesis is available via the Open Science Framework following this link: https://osf.io/wm62h/. The material contains raw and pre-processed data files, scripts for pre-processing and data analysis as well as audio files used as stimulus material for all experiments described in this thesis.

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Appendix

1. Appendix A - Stimulus material

Table A1

Critical German stimuli of Experiment 1 on the role of orthography in auditory priming

	Target	O+P+	O-P+	O-P-
1	Hohn	Lohn	Ton	Rat
2	Hören	Stören	Röhren	Raten
3	Paar	Haar	Zar	Berg
4	Krönen	Frönen	Dröhnen	Flicken
5	Führen	Rühren	Spüren	Tanzen
6	Bühne	Sühne	Düne	Weber
7	Fahl	Kahl	Schmal	Klein
8	Tor	Chor	Moor	Staub
9	Not	Lot	Boot	Stein
10	Spur	Kur	Tour	Leim
11	Tal	Qual	Zahl	Schiff
12	Schnee	Klee	Dreh	Huhn
13	Sieger	Flieger	Tiger	Schlange
14	Kuss	Nuss	Bus	Watt
15	Wiese	Fliese	Brise	Regel
16	Zählen	Wählen	Quälen	Pflegen
17	Bein	Schein	Hain	Null
18	Leid	Neid	Maid	Dill
19	Teich	Deich	Laich	Rock
20	Mai	Hai	Brei	Aal
21	Kreis	Reis	Mais	Heck

22	Seiher	Reiher	Leier	Flöte
23	Wachs	Lachs	Fax	Helm
24	Fuchs	Luchs	Jux	Fink
25	Beule	Keule	Fäule	Magen
26	Läuten	Häuten	Deuten	Merken
27	Kram	Scham	Rahm	Fleck
28	Spitze	Hitze	Skizze	Hammer
29	Stahl	Pfahl	Qual	Baum
30	Wenden	Spenden	Schänden	Fürchten
31	Nächte	Mächte	Rechte	Lieder
32	Dämmen	Kämmen	Hemmen	bieten
33	Bänder	Ränder	Sender	Katzen
34	Gelder	Felder	Wälder	Hefte
35	Menge	Enge	Länge	Teller
36	Wellen	Bellen	Fällen	Werfen
37	Berge	Zwerge	Särge	Wächter
38	Bart	Start	Fahrt	Seil
39	Tee	See	Reh	Lob
40	Mieter	Bieter	Liter	Leiche
41	Krise	Brise	Riese	Maler
42	Floh	Stroh	Zoo	Band
43	Sohn	Lohn	Ton	Hut
44	Krone	Zone	Bohne	Kater
45	Messe	Kresse	Nässe	Wetter
46	Wohnen	Lohnen	Schonen	Küssen

47	Dächer	Fächer	Becher	Brücken
48	Fieber	Schieber	Biber	Lampe
49	Kohle	Sohle	‡Bowle	Helfer
50	Feier	Leier	Reiher	Höhle
51	Wecker	Stecker	Bäcker	Bogen
52	Zeh	Reh	Fee	Dolch
53	Denken	Schwenken	Kränken	Reisen
54	Paaren	Haaren	Fahren	Schaukeln
55	Geier	Leier	Flyer	Vase
56	Taxen	Praxen	Achsen	Blätter
57	Scherz	Herz	März	Saft
58	Krieger	Flieger	Tiger	Tasse
59	Damen	Samen	Rahmen	Reste
60	Wut	Hut	Sud	Topf
61	Wert	Schwert	Herd	Ziel
62	Lord	Nord	Hort	Stift
63	Schoß	Floß	Moos	Kern
64	Kloß	Stoß	Moos	Bad
65	Job	Snob	Stopp	Blatt
66	Fluss	Nuss	Bus	Rost
67	Kind	Rind	Sprint	Pack
68	Mord	Nord	Sport	Fluch
69	Bahn	Wahn	Kran	Brot
70	Flug	Krug	Spuk	Stamm
71	Park	Mark	Sarg	Stuhl

72	Hahn	Wahn	Span	Trog
73	Laus	Maus	Strauß	Druck
74	Nähte	Drähte	Räte	Karten
75	Strähne	Mähne	Däne	Zwiebel
76	Fresser	Messer	Fässer	Dosen
77	Mut	Hut	Sud	Burg
78	‡Bug	Zug	Spuk	Traum
79	Schal	Gral	Saal	Wind
80	Kleid	Neid	Streit	Hass
81	Fuß	Ruß	Mus	Trumpf
82	Lehne	Sehne	Vene	Richter
83	Pferd	Herd	Schwert	Busch
84	Spaß	Fraß	Gas	Fisch
85	Fleiß	Schweiß	Preis	Bach
86	Strahl	Pfahl	Gral	Rand
87	Maat	Saat	Tat	Stern
88	Zahn	Wahn	Schwan	Lied
89	Schar	Bar	Haar	Lack
90	Hehl	Mehl	Gel	Tuch

Note. Stimuli marked with ‡ were excluded from analysis due to homophones/heterographs.

From “Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language”, by S. Türk and U. Domahs, 2022, *Brain and Language*, *235*, 105186, p. 11-12 (https://doi.org/10.1016/j.bandl.2022.105186). Copyright 2022 by Elsevier.

Table A2

English and German word and pseudoword stimuli of Experiments 1and 2 on unimodal and cross-modal TL priming

	English				**German**			
	Target	**TL**	**Control**	**Repetition**	**Target**	**TL**	**Control**	**Repetition**
				Non-identical cognates				
1	ACCENT	acnect	acmegt	accent	AKZENT	aknezt	akmest	akzent
2	BLOUSE	bsoule	bzoute	blouse	BLUSE	bsule	bzute	bluse
3	CLASS	csals	czats	class	KLASSE	ksalse	kzatse	klasse
4	FLEXIBLE	flebixle	fledivle	flexible	FLEXIBEL	flebixel	fledivel	flexibel
5	CLINIC	cnilic	cmitic	clinic	KLINIK	knilik	kmitik	klinik
6	CORRECT	corcert	corzept	correct	KORREKT	korkert	korfept	korrekt
7	CREDIT	cderit	cbepit	credit	KREDIT	kderit	kbepit	kredit
8	CRISIS	csiris	czibis	crisis	KRISE	ksire	kzibe	krise
9	DIRECT	dicert	digept	direct	DIREKT	dikert	difept	direkt
10	EFFECT	efceft	efgelt	effect	EFFEKT	efkeft	efhelt	effekt
11	EXACT	ecaxt	egavt	exact	EXAKT	ekaxt	ehavt	exakt
12	FLAME	fmale	fnate	flame	FLAMME	fmalme	fnatme	flamme
13	FRESH	fserh	fzebh	fresh	FRISCH	fsirch	fzibch	frisch
14	FRIEND	fnierd	fmiepd	friend	FREUND	fneurd	fmeupd	freund
15	GROUND	gnourd	gmoubd	ground	GRUND	gnurd	gmubd	grund
16	PALACE	pacale	pagafe	palace	PALAST	pasalt	pazaft	palast
17	PERCENT	pernect	permegt	percent	PROZENT	pronezt	promest	prozent
18	PHYSICS	psyhics	pzybics	physics	PHYSIK	psyhik	pzybik	physik
19	CONCERT	conrect	conpegt	concert	KONZERT	konrezt	konpest	konzert
20	PRESS	psers	pzebs	press	PRESSE	pserse	pzebse	presse
21	PRINCE	pnirce	pmipce	prince	PRINZ	pnirz	pmipz	prinz
22	PRIVATE	pvirate	pwibate	private	PRIVAT	pvirat	pwibat	privat

23	PRODUCT	pdoruct	pbopuct	product	PRODUKT	pdorukt	pbopukt	produkt
24	PROJECT	pjorect	plobect	project	PROJEKT	pjorekt	plobekt	projekt
25	PROVINCE	pvorince	pwobince	province	PROVINZ	pvorinz	pwobinz	provinz
26	RECORD	rerocd	repogd	record	REKORD	rerokd	repohd	rekord
27	DEBATE	detabe	delade	debate	DEBATTE	detabte	deladte	debatte
28	SPECIAL	scepial	sgerial	special	SPEZIELL	szepiell	ssebiell	speziell
29	STABLE	sbatle	sdafle	stable	STABIL	sbatil	sdafil	stabil
30	STORM	srotm	spolm	storm	STURM	srutm	spulm	sturm
31	STUDY	sduty	sbufy	study	STUDIE	sdutie	sbufie	studie
32	PROCESS	pcoress	pgobess	process	PROZESS	pzoress	psobess	prozess
33	CRITICAL	ctirical	cfipical	critical	KRITISCH	ktirisch	kfipisch	kritisch
34	DECADE	dedace	debage	decade	DEKADE	dedake	debahe	dekade
35	SHARP	srahp	sbakp	sharp	SCHARF	scrahf	scbakf	scharf
36	CRYSTAL	csyrtal	czyptal	crystal	KRISTALL	ksirtall	kziptall	kristall
37	BLONDE	bnolde	bmofde	blonde	BLOND	bnold	bmofd	blond
38	LICENSE	linecse	limegse	license	LIZENZ	linezz	limesz	lizenz
39	BROTHER	btorher	bfopher	brother	BRUDER	bdurer	bbuper	bruder
40	LEGEND	lenegd	lemecd	legend	LEGENDE	lenegde	lemecde	legende
41	ARTICLE	arcitle	argifle	article	ARTIKEL	arkitel	arhifel	artikel
42	FACADE	fadace	fabage	facade	FASSADE	fasdase	fasbaze	fassade
43	THOUSAND	thounasd	thoumazd	thousand	TAUSEND	taunesd	taumezd	tausend
44	PERFECT	perceft	pergelt	perfect	PERFEKT	perkeft	perhelt	perfekt
45	PLASTIC	psaltic	pzaftic	plastic	PLASTIK	psaltik	pzaftik	plastik
46	DISTANCE	disnatce	dismalce	distance	DISTANZ	disnatz	dismalz	distanz
47	CONTACT	concatt	congaft	contact	KONTAKT	konkatt	konhaft	kontakt
48	LANTERN	lanretn	lanpefn	lantern	LATERNE	laretne	lapefne	laterne
49	SPINACH	snipach	smibach	spinach	SPINAT	snipat	smibat	spinat
50	CRATER	ctarer	cfaper	crater	KRATER	ktarer	kfaper	krater
51	ACTION	atcion	algion	action	AKTION	atkion	alhion	aktion
52	ACTIVE	atcive	afgive	active	AKTIV	atkiv	afhiv	aktiv
53	CARTON	catron	cafpon	carton	KARTON	katron	kafpon	karton

54	THIRST	thisrt	thizbt	thirst	DURST	dusrt	duzbt	durst
55	CONFLICT	conlfict	contkict	conflict	KONFLIKT	konlfikt	kontkict	konflikt
56	CONCEPT	cocnept	cogmept	concept	KONZEPT	koznept	kosmept	konzept
57	STREET	srteet	spfeet	street	STRASSE	srtaße	spfaße	strasse
58	CENTRAL	cetnral	cefmral	central	ZENTRAL	zetnral	zefmral	zentral
59	CONGRESS	cognress	cocmress	congress	KONGRESS	kognress	kocmress	kongress
60	COMPLEX	comlpex	comfrex	complex	KOMPLEX	komlpex	komfrex	komplex
61	COSTUME	cotsume	colzume	costume	KOSTÜM	kotsüm	kolzüm	kostüm
62	CULTURE	cutlure	cufkure	culture	KULTUR	kutlur	kufkur	kultur
63	HUNGRY	hugnry	hucmry	hungry	HUNGRIG	hugnrig	hucmrig	hungrig
64	COMPLETE	comlpete	comfbete	complete	KOMPLETT	komlpett	komfbett	komplett
65	CONSTANT	cosntant	cozmtant	constant	KONSTANT	kosntant	kozmtant	konstant
66	EXTREME	exrteme	expleme	extreme	EXTREM	exrtem	explem	extrem
67	FACTOR	fatcor	falgor	factor	FAKTOR	fatkor	falbor	faktor
68	GARDEN	gadren	gabpen	garden	GARTEN	gatren	gafpen	garten
69	HUNDRED	hudnred	hubmred	hundred	HUNDERT	hudnert	hubmert	hundert
70	IMPULSE	ipmulse	ibnulse	impulse	IMPULS	ipmuls	ibnuls	impuls
71	INSECT	isnect	izmect	insect	INSEKT	isnekt	izmekt	insekt
72	LENSE	lesne	lezme	lense	LINSE	lisne	lizme	linse
73	ATHLETE	atlhete	atfkete	athlete	ATHLET	atlhet	atfket	athlet
74	NERVOUS	nevrous	nenbous	nervous	NERVÖS	nevrös	nenbös	nervös
75	OBJECT	ojbect	olpect	object	OBJEKT	ojbekt	olpekt	objekt
76	PERFUME	pefrume	pelpume	perfume	PARFUEM	pafrüm	palpüm	parfuem
77	RESPECT	repsect	rebzect	respect	RESPEKT	repsekt	rebzekt	respekt
78	SCANDAL	scadnal	scabmal	scandal	SKANDAL	skadnal	skabmal	skandal
79	SILVER	sivler	siwter	silver	SILBER	sibler	sidter	silber
80	STRIKE	srtike	spfike	strike	STREIK	srteik	spfeik	streik
81	TEMPLE	tepmle	tebnle	temple	TEMPEL	tepmel	tebnel	tempel
82	UNCLE	ucnle	ugmle	uncle	ONKEL	oknel	ofmel	onkel
83	WONDER	wodner	wobmer	wonder	WUNDER	wudner	wubmer	wunder
84	CONTRAST	conrtast	conplast	contrast	KONTRAST	konrtast	konplast	kontrast

85	STRAW	srtaw	sblaw	straw	STROH	srtoh	sbloh	stroh
86	CONSOLE	cosnole	cozmole	console	KONSOLE	kosnole	kozmole	konsole
87	SHRINE	srhine	spkine	shrine	SCHREIN	scrhein	scpkein	schrein
88	ADDRESS	adrdess	adpbess	address	ADRESSE	ardesse	apbesse	adresse
89	SHOULDER	shoudler	shoubfer	shoulder	SCHULTER	schutler	schuhfer	schulter
90	SCHOOL	shcool	skgool	school	SCHULE	shcule	skgule	schule
91	CIRCUS	cicrus	cigpus	circus	ZIRKUS	zikrus	zihpus	zirkus
92	INSTINCT	intsinct	inlzinct	instinct	INSTINKT	intsinkt	inlzinkt	instinkt
93	ANGER	agner	acmer	anger	AERGER	ägrer	äcper	ärger
94	BRIDGE	brigde	bricbe	bridge	BRUECKE	brükce	brühge	brücke
95	DAUGHTER	daugther	dauglber	daughter	TOCHTER	tocther	toclber	tochter
96	SOLDIER	sodlier	sobtier	soldier	SOLDAT	sodlat	sobtat	soldat
97	JACKET	jakcet	jafget	jacket	JACKE	jakce	jafge	jacke
98	TRUMPET	trupmet	trurnet	trumpet	TROMPETE	tropmete	trornete	trompete
99	TROPHY	trohpy	trofby	trophy	TROPHAEE	trohpäe	trofbäe	trophäe
100	WINDY	widny	wibmy	windy	WINDIG	widnig	wibmig	windig
101	AUTHOR	atuhor	alohor	author	AUTOR	atuor	aloor	autor
102	CANAL	cnaal	cmeal	canal	KANAL	knaal	kmeal	kanal
103	CELLAR	clelar	ctalar	cellar	KELLER	kleler	ktaler	keller
104	COFFEE	cfofee	cpefee	coffee	KAFFEE	kfafee	kpefee	kaffee
105	FATHER	ftaher	fleher	father	VATER	vtaer	vleer	vater
106	CROWN	corwn	cupwn	crown	KRONE	korne	kupne	krone
107	GUITAR	gutiar	gufear	guitar	GITARRE	gtiarre	gfearre	gitarre
108	LOGIC	lgoic	lcuic	logic	LOGIK	lgoik	lcuik	logik
109	MAGIC	mgaic	mceic	magic	MAGIE	mgaie	mceie	magie
110	FOCUS	fcous	fguus	focus	FOKUS	fkous	fhuus	fokus
111	MOTIVE	moitve	moelve	motive	MOTIV	moitv	moelv	motiv
112	MUSIC	msuic	mzoic	music	MUSIK	msuik	mzoik	musik
113	NATURE	nautre	naofre	nature	NATUR	nautr	naofr	natur
114	NUMBER	nmuber	nnober	number	NUMMER	nmumer	nnomer	nummer
115	OCEAN	oecan	oagan	ocean	OZEAN	oezan	oasan	ozean

116	PAPER	paepr	paabr	paper	PAPIER	paiper	paeber	papier
117	SALAD	slaad	stiad	salad	SALAT	slaat	stiat	salat
118	MOBILE	moible	moedle	mobile	MOBIL	moibl	moedl	mobil
119	SERIES	seires	seapes	series	SERIE	seire	seape	serie
120	CHEMICAL	chmeical	chnaical	chemical	CHEMISCH	chmeisch	chnaisch	chemisch
121	WOUND	wonud	womod	wound	WUNDE	wnude	wmode	wunde
122	SHAME	sahme	sebme	shame	SCHAM	scahm	scebm	scham
123	SPEAR	separ	sirar	spear	SPEER	seper	sirer	speer
124	NAVEL	nvael	nweel	navel	NABEL	nbael	nheel	nabel
125	CHAMBER	chmaber	chneber	chamber	KAMMER	kmamer	knemer	kammer
126	GROUP	gorup	gubup	group	GRUPPE	gurppe	gobppe	gruppe
127	JEWEL	jweel	jvael	jewel	JUWEL	jwuel	jvoel	juwel
128	WEATHER	wetaher	wefeher	weather	WETTER	wteter	wfater	wetter
129	WHILE	whlie	whfee	while	WEILE	welie	wefee	weile
130	POUND	ponud	pomod	pound	PFUND	pfnud	pfmod	pfund
131	WAGON	wgaon	wceon	wagon	WAGEN	wgaen	wceen	wagen
132	PEPPER	ppeper	pbaper	pepper	PFEFFER	pffefer	pfhafer	pfeffer
133	GHOST	ghsot	ghzut	ghost	GEIST	gesit	gezet	geist
134	BROWN	borwn	bupwn	brown	BRAUN	barun	bepun	braun
135	MACHINE	machnie	machmee	machine	MASCHINE	maschnie	maschmee	maschine
136	WATER	wtaer	wfeer	water	WASSER	wsaser	wzeser	wasser
137	DREAM	deram	dapam	dream	TRAUM	tarum	tepum	traum
138	STEEL	setel	safel	steel	STAHL	sathl	sefhl	stahl
139	THUNDER	thnuder	thmoder	thunder	DONNER	dnoner	dmuner	donner
140	PIRATE	priate	pbeate	pirate	PIRAT	priat	pbeat	pirat
141	SECURE	sceure	sgaure	secure	SICHER	sciher	sgeher	sicher
142	CIPHER	cpiher	cbeher	cipher	ZIFFER	zfifer	ztefer	ziffer
143	SUGAR	sguar	scoar	sugar	ZUCKER	zcuker	zgoker	zucker
144	NEEDLE	nedele	nebale	needle	NADEL	ndael	nbeel	nadel
145	CARROT	crarot	cperot	carrot	KAROTTE	kraotte	kpeotte	karotte
146	COAST	cosat	cozet	coast	KUESTE	ksüte	kzöte	küste

147	SHIELD	shiled	shitad	shield	SCHILD	schlid	schted	schild
148	SEVEN	sveen	swaen	seven	SIEBEN	sibeen	sidaen	sieben
149	PRICE	pirce	pebce	price	PREIS	peris	pibis	preis
150	KNUCKLE	kunckle	komckle	knuckle	KNOECHEL	könchel	kümchel	knöchel
Translation-equivalent non-cognates								
1	FUTURE	furute	fusule	future	ZUKUNFT	zunukft	zusulft	zukunft
2	FOLLOWED	folwoled	folvoked	followed	VERFOLGT	verlofgt	vertokgt	verfolgt
3	ORCHARD	ohcrard	ofcpard	orchard	OBSTHAIN	otsbhain	ofsphain	obsthain
4	IMPRINT	impnirt	impmipt	imprint	ABDRUCK	abdcurk	abdgupk	abdruck
5	CLOTH	ctolh	cfoth	cloth	STOFF	sfotf	slodf	stoff
6	ANSWER	awsner	avsmer	answer	ANTWORT	awtnort	avtmort	antwort
7	DOCILE	dolice	dofige	docile	FOLGSAM	fosglam	fozgfam	folgsam
8	SPIDER	sdiper	sbirer	spider	SPINNE	snipne	smirne	spinne
9	INTAKE	inkate	inbale	intake	ZUFUHR	zuhufr	zubulr	zufuhr
10	BLUNT	bnult	bmuft	blunt	STUMPF	smutpf	snufpf	stumpf
11	INVENTOR	innevtor	inmewtor	inventor	ERFINDER	ernifder	ermihder	erfinder
12	ENRAGED	engared	encaped	enraged	ERZUERNT	errüznt	erpüsnt	erzuernt
13	TWITCHY	twihcty	twibcfy	twitchy	ZAPPELIG	zaplepig	zapterig	zappelig
14	BENEFIT	befenit	belemit	benefit	GEFALLEN	gelaflen	getaklen	gefallen
15	NECKLACE	neckcale	neckgate	necklace	HALSBAND	halsnabd	halsmapd	halsband
16	PARENTS	panerts	pamepts	parents	ELTERN	elretn	elpefn	eltern
17	KNOCKER	kconker	kgomker	knocker	KLOPFER	kpolfer	kbotfer	klopfer
18	PROSPECT	proscept	prosgert	prospect	AUSBLICK	ausbcilk	ausbgifk	ausblick
19	JUMBLE	julbme	jufbne	jumble	RAMSCH	racsmh	ragsnh	ramsch
20	ARRIVAL	arviral	arwipal	arrival	ANKUNFT	annukft	anmubft	ankunft
21	LINKAGE	lingake	lincabe	linkage	GESTAENGE	gesnätge	gesmäfge	gestaenge
22	ANNOYED	anyoned	anvomed	annoyed	GENERVT	gerenvt	gepemvt	genervt
23	BRACKET	bcarket	bgabket	bracket	KLAMMER	kmalmer	knatmer	klammer
24	OUTCAST	outsact	outzagt	outcast	GEAECHTET	geäthcet	geälhget	geaechtet
25	BRASS	bsars	bzaps	brass	BLECH	bcelh	bgefh	blech
26	BLOTCH	btolch	bfotch	blotch	KLECKS	kcelks	kgetks	klecks

27	CAREFREE	caferee	catebee	carefree	SORGLOS	solgros	sotgbos	sorglos
28	PRUDENCE	prunedce	prumebce	prudence	VORSICHT	vorcisht	vorgizht	vorsicht
29	MADNESS	madsens	madzems	madness	IRRSINN	irrnisn	irrmizn	irrsinn
30	CHUNK	cnuhk	cmubk	chunk	KLOTZ	ktolz	kfotz	klotz
31	BETRAYED	betyared	betvaped	betrayed	BETROGEN	betgoren	betcopen	betrogen
32	CREVICE	cverice	cwebice	crevice	SPALTE	slapte	sfabte	spalte
33	DAMAGE	dagame	dacane	damage	SCHADEN	scdahen	scbaken	schaden
34	DELIGHT	degilht	decifht	delight	GENUSS	gesuns	gezums	genuss
35	GRUDGE	gdurge	gbupge	grudge	GROLL	glorl	gfopl	groll
36	DURABLE	dubarle	dudaple	durable	HALTBAR	habtlar	hadtfar	haltbar
37	EDIBLE	ebidle	ehikle	edible	ESSBAR	ebssar	ehszar	essbar
38	MENACE	mecane	megame	menace	GEFAHR	gehafr	gebalr	gefahr
39	FAILURE	fairule	faipute	failure	AUSFALL	auslafl	austakl	ausfall
40	FAREWELL	fawerell	favepell	farewell	LEBEWOHL	lewebohl	levedohl	lebewohl
41	FLASH	fsalh	fzath	flash	BLITZ	btilz	bkifz	blitz
42	FOOLISH	foosilh	foozifh	foolish	DAEMLICH	dämcilh	dämgifh	daemlich
43	NUISANCE	nuinasce	nuimazce	nuisance	STOERUNG	stönurg	stömupg	stoerung
44	MESSAGE	mesgase	mescaze	message	MELDUNG	melnudg	melmubg	meldung
45	MODEST	mosedt	mozebt	modest	ZUECHTIG	züthcig	züfhgig	zuechtig
46	GLOSS	gsols	gzofs	gloss	GLANZ	gnalz	gmafz	glanz
47	PAVEMENT	pamevent	panewent	pavement	GEHSTEIG	getsheig	gelskeig	gehsteig
48	GUIDANCE	guinadce	guimabce	guidance	FUEHRUNG	führurg	fühmupg	fuehrung
49	SCRAMBLE	scmarble	scnapble	scramble	GERANGEL	genargel	gemapgel	gerangel
50	HATCHET	hahctet	habclet	hatchet	HANDBEIL	habdneil	hahdmeil	handbeil
51	WINDOW	widnow	wibmow	window	FENSTER	fesnter	fezmter	fenster
52	HARNESS	hanress	hampess	harness	GESCHIRR	gecshirr	gegchirr	geschirr
53	HARVEST	havrest	hawpest	harvest	ERTRAG	errtag	erphag	ertrag
54	PUMPKIN	pupmkin	purnkin	pumpkin	KUERBIS	kübris	küpkis	kuerbis
55	HEEDFUL	heefdul	heehbul	heedful	ACHTSAM	achstam	achzlam	achtsam
56	MONGER	mogner	mocmer	monger	HAENDLER	hädnler	häbmer	haendler
57	HEIRLOOM	heilroom	heitpoom	heirloom	ERBSTUECK	erbtsück	erblzück	erbstueck

58	POCKET	pokcet	pohget	pocket	TASCHE	tacshe	tagzhe	tasche
59	CANDLE	cadnle	cabmle	candle	KERZE	kezre	kespe	kerze
60	RAMPAGE	rapmage	rarnage	rampage	RANDALE	radnale	rabmale	randale
61	EXAMPLE	exapmle	exarnle	example	BEISPIEL	beipsiel	beirziel	beispiel
62	MISTAKE	mitsake	milzake	mistake	FEHLER	felher	fetker	fehler
63	OUTCOME	ouctome	ouglome	outcome	AUSGANG	augsang	auczang	ausgang
64	HUMBLE	hubmle	hupnle	humble	AERMLICH	ärlmich	ärtnich	aermlich
65	HUNCH	hucnh	hugmh	hunch	BUCKEL	bukcel	buhgel	buckel
66	TEMPLATE	tepmlate	ternlate	template	VORLAGE	volrage	votpage	vorlage
67	SURVEY	suvrey	suwpey	survey	UMFRAGE	umrfage	umphage	umfrage
68	INCREASE	inrcease	inpgease	increase	MEHRUNG	merhung	mepfung	mehrung
69	AIRPLANE	airlpane	airtrane	airplane	FLUGZEUG	fluzgeug	flusceug	flugzeug
70	AMBITION	abmition	apnition	ambition	EHRGEIZ	erhgeiz	epkgeiz	ehrgeiz
71	MOISTURE	moitsure	moilzure	moisture	FEUCHTE	feuhcte	feukgte	feuchte
72	CATCHER	cacther	cagler	catcher	FAENGER	fägner	fäcmer	faenger
73	MAGPIE	mapgie	mabcie	magpie	ELSTER	eltser	elhzer	elster
74	CONDUCT	codnuct	cobmuct	conduct	BETRAGEN	bertagen	bephagen	betragen
75	LATCHED	lacthed	laglhed	latched	GESPERRT	gepserrt	gercerrt	gesperrt
76	INGRESS	inrgess	inpcess	ingress	EINTRITT	eitnritt	eilmritt	eintritt
77	CUSHION	cuhsion	cukzion	cushion	POLSTER	poslter	pozkter	polster
78	DESCENT	decsent	degzent	descent	ABSTIEG	abtsieg	ablzieg	abstieg
79	SICKNESS	sicnkess	sicmhess	sickness	UEBELKEIT	übekleit	übehteit	uebelkeit
80	DISGUST	digsust	diczust	disgust	ABSCHEU	abcsheu	abgzheu	abscheu
81	DUNGEON	dugneon	ducmeon	dungeon	VERLIES	velries	vetpies	verlies
82	INVOKED	ivnoked	iwmoked	invoked	ERFLEHT	efrleht	ehpleht	erfleht
83	ESTEEM	etseem	elzeem	esteem	ANSEHEN	asnehen	azmehen	ansehen
84	EXPENSE	epxense	erhense	expense	UNKOSTEN	uknosten	uhmosten	unkosten
85	FILTHY	filhty	filkly	filthy	DRECKIG	drekcig	drehgig	dreckig
86	BOTTLE	botlte	bothfe	bottle	FLASCHE	flacshe	flagzhe	flasche
87	LAUNDRY	laudnry	laubmry	laundry	WAESCHE	wäshce	wäsfge	waesche
88	FORTRESS	fotrress	folpress	fortress	FESTUNG	fetsung	felzung	festung

89	FORTUNE	fotrune	fohpune	fortune	GESCHICK	gecshick	gegzhick	geschick
90	FOUNDER	foudner	foubmer	founder	GRUENDER	grüdner	grübmer	gruender
91	JESTER	jetser	jelzer	jester	HOFNARR	honfarr	homharr	hofnarr
92	LECTURE	letcure	lefgure	lecture	VORTRAG	votrrag	volprag	vortrag
93	VENTURE	vetnure	velmure	venture	WAGNIS	wangis	wamcis	wagnis
94	GAMBLER	gabmler	gadnler	gambler	ZOCKER	zokcer	zohger	zocker
95	KINDRED	kidnred	kibmred	kindred	VERWANDT	vewrandt	vevpandt	verwandt
96	GENTLE	getnle	gefmle	gentle	SANFT	safnt	satmt	sanft
97	GOBLET	golbet	gotdet	goblet	KELCH	keclh	kegth	kelch
98	GRUMPY	grupmy	grubny	grumpy	GRANTIG	gratnig	grafmig	grantig
99	HARDSHIP	hadrship	habpship	hardship	NOTLAGE	noltage	nohfage	notlage
100	HARLOT	halrot	hatpot	harlot	DIRNE	dinre	dimpe	dirne
101	GIANT	ginat	gimet	giant	RIESE	risee	rizae	riese
102	DESERT	dseert	dzoert	desert	WUESTE	wsüte	wzöte	wueste
103	CIRCLE	cricle	cpucle	circle	KREIS	keris	kopis	kreis
104	DRESS	derss	dopss	dress	KLEID	kelid	kotid	kleid
105	CLOUD	colud	cutud	cloud	WOLKE	wloke	wtuke	wolke
106	BREADTH	beradth	bapadth	breadth	BREITE	berite	bapite	breite
107	RIVER	rvier	rwaer	river	FLUSS	fulss	fotss	fluss
108	BUCKET	bcuket	bgoket	bucket	EIMER	emier	enaer	eimer
109	VESSEL	vsesel	vzasel	vessel	GEFAESS	gfeäß	ghaäß	gefaess
110	VIRTUE	vritue	vpatue	virtue	TUGEND	tguend	tcoend	tugend
111	BUBBLE	bbuble	bdoble	bubble	BLASE	balse	betse	blase
112	COMMAND	cmomand	cnumand	command	BEFEHL	bfeehl	bhaehl	befehl
113	CRAYON	caryon	cepyon	crayon	KREIDE	keride	kapide	kreide
114	BASIN	bsain	bzein	basin	BECKEN	bceken	bgaken	becken
115	BUTTON	btuton	bfoton	button	KNOPF	konpf	kumpf	knopf
116	MORSEL	mrosel	mpusel	morsel	BISSEN	bsisen	bzasen	bissen
117	SUMMIT	smumit	snomit	summit	GIPFEL	gpifel	grafel	gipfel
118	POLITE	ploite	ptuite	polite	HOEFLICH	hfölich	hlülich	hoeflich
119	FIBER	fbier	fdaer	fiber	FASER	fsaer	fzeer	faser

120	SUPPLY	spuply	sruply	supply	VORRAT	vrorat	vpurat	vorrat
121	LONELY	lnoely	lmuely	lonely	EINSAM	enisam	emasam	einsam
122	BROOM	borom	bupom	broom	BESEN	bseen	bzaen	besen
123	PROUD	porud	pubud	proud	STOLZ	sotlz	suflz	stolz
124	PAGEANT	pgaeant	pceeant	pageant	FESTZUG	fsetzug	fzatzug	festzug
125	STAGE	satge	selge	stage	BUEHNE	bhüne	bföne	buehne
126	PILLOW	plilow	ptalow	pillow	KISSEN	ksisen	kzasen	kissen
127	SOUND	sonud	somod	sound	KLANG	klnag	klmeg	klang
128	CROSS	corss	cupss	cross	KREUZ	keruz	kabuz	kreuz
129	TENSION	tnesion	tmasion	tension	SPANNUNG	sapnnung	sernnung	spannung
130	TISSUE	tsisue	tzasue	tissue	GEWEBE	gweebe	gvaebe	gewebe
131	GRIEF	giref	gapef	grief	TRAUER	taruer	tepuer	trauer
132	FUNNY	fnuny	fmony	funny	LUSTIG	lsutig	lzotig	lustig
133	FAMOUS	fmaous	fneous	famous	BERUEHMT	breühmt	bpaühmt	beruehmt
134	GOBLIN	gbolin	gpulin	goblin	KOBOLD	kboold	kpuold	kobold
135	DEVICE	dveice	dwaice	device	GERAET	greät	gpaät	geraet
136	DRIVER	dirver	dabver	driver	FAHRER	fharer	fterer	fahrer
137	FRAME	farme	fepme	frame	RAHMEN	rhamen	rfemen	rahmen
138	FREEDOM	feredom	fapedom	freedom	FREIHEIT	feriheit	fapiheit	freiheit
139	HUNTER	hnuter	hmoter	hunter	JAEGER	jgäer	jcöer	jaeger
140	GUILT	gulit	gutat	guilt	SCHULD	scuhld	scofld	schuld
141	WEDDING	wdeding	wbading	wedding	HOCHZEIT	hcohzeit	hguhzeit	hochzeit
142	NOTION	ntoion	nluion	notion	BEGRIFF	bgeriff	bcariff	begriff
143	OPINION	opniion	opmaion	opinion	MEINUNG	meniung	memaung	meinung
144	PATTERN	ptatern	pletern	pattern	MUSTER	msuter	mzoter	muster
145	BORDER	broder	bpuder	border	GRENZE	gernze	gapnze	grenze
146	PLAYER	palyer	petyer	player	SPIELER	sipeler	sareler	spieler
147	PRAYER	paryer	pebyer	prayer	GEBET	gbeet	gdaet	gebet
148	DREADFUL	deradful	dapadful	dreadful	GRAUSIG	garusig	gepusig	grausig
149	REVIEW	rveiew	rwaiew	review	PRUEFUNG	pürfung	pöbfung	pruefung
150	TRAFFIC	tarffic	tepffic	traffic	VERKEHR	vrekehr	vpakehr	verkehr

Pseudowords								
1	SICTURE	sirtuce	siptuge	sicture	LAFENT	laneft	lameht	lafent
2	DILAGE	digale	dicate	dilage	PRAUSE	psaure	pzaube	prause
3	CRIDGE	cdirge	clibge	cridge	KNOLEM	klonem	ktomem	knolem
4	GNASE	gsane	gzame	gnase	PFUNEL	pnufel	pmuhel	pfunel
5	SHRIVER	shvirer	shwiper	shriver	DAMGRAT	dargmat	dapgwat	damgrat
6	PADULT	paludt	patuft	padult	RALKWIT	rawklit	ravktit	ralkwit
7	GLANE	gnale	gmate	glane	BRUNTE	bnurte	bmopte	brunte
8	CHOSREN	csohren	czobren	chosren	KLENTE	knelte	kmefte	klente
9	DRUBLEM	dlubrem	dfubpem	drublem	TRUSE	tsure	tzupe	truse
10	POLLAGE	polgale	polcate	pollage	KRUNTE	ktunre	klunbe	krunte
11	GLANNER	gnalner	gmatner	glanner	BLINO	bnilo	bmito	blino
12	HOSERT	horest	hopezt	hosert	BROELOP	blörop	btöbop	broelop
13	ROPERT	rorept	robedt	ropert	BROFEL	bforel	bhopel	brofel
14	STROLEY	slrotey	skrofey	stroley	BRUNFEL	bfunrel	btunpel	brunfel
15	STAME	smate	snafe	stame	PRAETE	ptäre	pfäbe	praete
16	LOMSTER	lotsmer	lofsner	lomster	GRULTE	glurte	gtupte	grulte
17	CLOURISH	croulish	cpoutish	clourish	FRINKE	fnirke	fmipke	frinke
18	PRATINE	ptarine	pfabine	pratine	GLOST	gsolt	gzoft	glost
19	MIRALD	milard	mifapd	mirald	FROSPE	fsorpe	fzobpe	frospe
20	GLIRAINE	grilaine	gbifaine	gliraine	GLEIPE	gpeile	greite	gleipe
21	TRUMWOT	twumrot	tmumpot	trumwot	FLABEN	fbalen	fdafen	flaben
22	ATLOMS	atmols	atwofs	atloms	GRATEN	gtaren	glaben	graten
23	ERNLATS	ertlans	erflams	ernlats	TRUELICH	tlürich	tfübich	truelich
24	BRONIP	bnorip	bmobip	bronip	PFEBER	pbefer	pdeter	pfeber
25	GLINSEP	gsinlep	gzintep	glinsep	BLETE	btele	bfejen	blete
26	NASHOFS	nafhoss	nathozs	nashofs	KLUME	kmule	knufe	klume
27	DENSIPED	denpised	denbized	densiped	SPUME	smupe	snube	spume
28	GROTHEM	gtorhen	glophen	grothem	TANORE	tarone	tapome	tanore
29	TRINTER	tnirter	tmipter	trinter	WEROKE	wekore	wefobe	weroke
30	NORMSTOK	nosmrtok	nozmptok	normstok	PRUME	pmure	pnube	prume

31	SUITCAST	suitsact	suitzagt	suitcast	KLAFE	kfale	kpate	klafe
32	FLORTY	frolty	fpofty	florty	SCHROLE	schlore	schtope	schrole
33	TORMEST	torsemt	torzent	tormest	GRIELE	gliere	gfiebe	griele
34	CRASHINE	chasrine	ckaspine	crashine	BULASE	busale	buzate	bulase
35	PRAZY	pzary	psaby	prazy	SPUWE	swupe	svufe	spuwe
36	MACTATE	mattace	maftage	mactate	KLOFE	kfole	kpote	klofe
37	FRINGELY	fnirgely	fmipgely	fringely	GRUSEN	gsuren	gzupen	grusen
38	STICTOM	scittom	sgiltom	stictom	TROCHT	tcorht	tgopht	trocht
39	COLSTRY	corstly	cobstfy	colstry	STOHM	shotm	sfolm	stohm
40	FABTRY	fartby	faptdy	fabtry	PRAGEL	pgarel	pcabel	pragel
41	PRONCEL	pnorcel	pmobcel	proncel	SCHALPER	sclahper	scfabper	schalper
42	CURFANT	curnaft	curmalt	curfant	KLUPER	kpuler	krufer	kluper
43	BLAVET	bvalet	bwaket	blavet	KNASTER	ksanter	kzamter	knaster
44	MOSTERN	mosretn	mospefn	mostern	HOLMPER	hopmler	hobmfer	holmper
45	TOUSURE	touruse	toupuze	tousure	PFUERME	prüfme	pbülme	pfuerme
46	NUMPKIT	nukpmit	nufpnit	numpkit	STURGEL	srutgel	spufgel	sturgel
47	RAGNURE	ragrune	ragpume	ragnure	SPURLE	sruple	sbufle	spurle
48	DURFNESS	dunfress	dumfpess	durfness	TRAERCHEL	trähcrel	träfcpel	traerchel
49	KEARLESS	kearsels	kearzefs	kearless	DORAST	dosart	dozabt	dorast
50	PROLEMN	ploremn	ptobemn	prolemn	BLORST	brolst	bpotst	blorst
51	GATTLE	gatlte	gatfhe	gattle	PAKLA	palka	patfa	pakla
52	RANTLER	ratnler	ralmler	rantler	LASNA	lansa	lamza	lasna
53	DOSTOR	dotsor	dolzor	dostor	MARNEL	manrel	mambel	marnel
54	MINLOW	milnow	mifmow	minlow	REKTRO	retkro	reldro	rektro
55	DAPTAN	datpan	dafran	daptan	BALPMO	balmpo	balnro	balpmo
56	FASCOR	facsor	fagzor	fascor	PRISTEL	pritsel	prilzel	pristel
57	GISTLE	gitsle	gilzle	gistle	BALTENK	batlenk	bapkenk	baltenk
58	DOPTER	dotper	dafber	dopter	KRUSPEL	krupsel	krubzel	kruspel
59	ENSINE	esnine	ezmine	ensine	MATLEM	maltem	mafhem	matlem
60	FORNER	fonrer	fomber	forner	SERTAU	setrau	selpau	sertau
61	GARLEP	galrep	gatpep	garlep	MUNKE	mukne	mufme	munke

62	RUPTAIN	rutpain	ruldain	ruptain	RALTE	ratle	rafke	ralte
63	BILMING	bimling	binting	bilming	FULPE	fuple	fubte	fulpe
64	PARLICK	palrick	patbick	parlick	NIRLE	nilre	nifpe	nirle
65	SINDOUR	sidnour	sipmour	sindour	STELKE	stekle	stehte	stelke
66	MALTROW	malrtow	malpfow	maltrow	SAMPE	sapme	sarne	sampe
67	GARWOT	gawrot	gavbot	garwot	POGLIS	polgis	pofcis	poglis
68	NUSTER	nutser	nufzer	nuster	RAPKE	rakpe	rafbe	rapke
69	CARKOT	cakrot	catbot	carkot	GIRBEL	gibrel	gidpel	girbel
70	PIGMURE	pimgure	pincure	pigmure	GUMPE	gupme	gubne	gumpe
71	REFLOP	relfop	rethop	reflop	LORTE	lotre	lofpe	lorte
72	PIGHT	pihgt	pikct	pight	PROMPE	propme	prorne	prompe
73	TRIDGE	trigde	tricbe	tridge	JASTEN	jatsen	jafzen	jasten
74	TINSER	tisner	tizmer	tinser	NARFE	nafre	nakbe	narfe
75	LUNTLE	lutnle	lufmle	luntle	MARBEN	mabren	madpen	marben
76	NISTLE	nislte	nisfhe	nistle	RINSE	risne	rizme	rinse
77	THREAM	trheam	tpfeam	thream	GAMPE	gapme	gabne	gampe
78	PALCUTS	pacluts	pagjuts	palcuts	FEKTE	fetke	felhe	fekte
79	LUMHON	luhmon	lufnon	lumhon	TUNGE	tugne	tucme	tunge
80	DRIDGE	drigde	dricpe	dridge	WUPFER	wufper	wutber	wupfer
81	WADLY	waldy	watby	wadly	NATZE	nazte	nasle	natze
82	ABSEY	asbey	azdey	absey	GANTEL	gatnel	galmel	gantel
83	CLETBAN	clebtan	clepfan	cletban	LORKE	lokre	lofpe	lorke
84	TRASLER	tralser	trafzer	trasler	MINKE	mikne	mifme	minke
85	FIETLY	fielty	fiefhy	fietly	KANGER	kagner	kacmer	kanger
86	GROPTION	grotpion	grolrion	groption	SUMPEL	supmel	sufnel	sumpel
87	LAPTION	latpion	lalbion	laption	MORLE	molre	motbe	morle
88	PRISTION	pritsion	prilzion	pristion	LASPEL	lapsel	labzel	laspel
89	SALMORT	samlort	sanfort	salmort	TORGEN	togren	tocben	torgen
90	TOWLY	tolwy	totvy	towly	STIPTE	stitpe	stifre	stipte
91	SULVER	suvler	suwfer	sulver	RINZANG	riznang	rismang	rinzang
92	PURPER	pupres	pudber	purper	BLETZOR	bleztor	blesfor	bletzor

93	LONDER	lodner	lobmer	londer	STRULE	srtule	splule	strule
94	DUNCTION	duntcion	dunfcion	dunction	PFLASKE	pflakse	pflafze	pflaske
95	MICTURE	mitcure	mifgure	micture	ROEMSEL	rösmel	röznel	roemsel
96	PINCEL	picnel	pigmel	pincel	ZURSEL	zusrel	zuzpel	zursel
97	PENTLET	petnlet	pemflet	pentlet	KROPSEL	krospel	krozbel	kropsel
89	PERNEFT	penreft	pempeft	perneft	MEUTLUNG	meultung	meufhung	meutlung
99	FROTRALT	frortalt	froplalt	frotralt	DREISNIG	dreinsig	dreimzig	dreisnig
100	PRILNESS	prinless	primfess	prilness	PILMER	pimler	pinfer	pilmer
101	HOUNE	honue	homae	houne	LAUKE	lakue	lalie	lauke
102	DOMAST	doamst	douwst	domast	AMKULA	amklua	amktoa	amkula
103	GREAL	geral	gipal	greal	LOMBEDO	lombdeo	lombcio	lombedo
104	GEVIL	gveil	gwail	gevil	RATOGEN	ratgoen	ratcuen	ratogen
105	GURGER	gruger	gboger	gurger	MALTOR	mlator	mtetor	maltor
106	SHROUP	shorup	shubup	shroup	RATIMES	ratmies	ratnees	ratimes
107	LIFED	lfied	lheed	lifed	REKSUP	rkesup	rfasup	reksup
108	TINGER	tniger	tmeger	tinger	KATARP	katrap	katbop	katarp
109	GARTY	graty	gpoty	garty	MARSILE	mrasile	mpusile	marsile
110	DROGRAM	drogarm	drogubm	drogram	SOLTERN	slotern	stutern	soltern
111	TOINED	tonied	tomeed	toined	RAMIT	rmait	rnoit	ramit
112	KEALORD	kealrod	kealpud	kealord	PAREL	prael	pbeel	parel
113	PROCEAN	porcean	pubcean	procean	MIFAS	mfias	mteas	mifas
114	LEAMY	lemay	lenoy	leamy	ROKEL	rkoel	rhuel	rokel
115	LURDY	lrudy	lpody	lurdy	HOEMEL	hmöel	hnüel	hoemel
116	PROTOKE	portoke	puptoke	protoke	KUTAS	ktuas	kfoas	kutas
117	CRATCH	cartch	cubtch	cratch	MEKIS	mkeis	mbais	mekis
118	SNEEL	senel	simel	sneel	GUPER	gpuer	gboer	guper
119	TARDON	tradon	tpidon	tardon	WANTNIS	wnatnis	wmutnis	wantnis
120	GRICKLE	girckle	gapckle	grickle	LUETENG	ltüeng	lföeng	lueteng
121	ZIPPLER	zpipler	zbepler	zippler	FETTELN	fettlen	fettkun	fetteln
122	LOBBER	lobebr	lobadr	lobber	KILDER	kiledr	kilibr	kilder
123	NORIAL	noiral	noepal	norial	GEITE	getie	gefee	geite

124	DOBOT	doobt	doapt	dobot	BINKEN	bniken	bmeken	binken
125	PEHEARCH	peherach	pehebich	pehearch	KASEN	ksaen	kzeen	kasen
126	MEDEMBER	medmeber	medwiber	medember	TALZER	tlazer	tfezer	talzer
127	WOOBIG	wooibg	wooepg	woobig	RANGOR	rnagor	rmigor	rangor
128	SEPROACH	seporach	sepubach	seproach	HANZER	hnazer	hmezer	hanzer
129	GRELF	gerlf	giblf	grelf	LARTE	lrate	lpite	larte
130	TROBIDE	trobdie	trobrae	trobide	GODEN	gdoen	gbuen	goden
131	SABEL	sbael	sreel	sabel	RUNIK	rnuik	rmoik	runik
132	SIRECT	sircet	sirgat	sirect	MAFTE	mfate	mlite	mafte
133	CROJECT	corject	cubject	croject	SIROL	sriol	speol	sirol
134	LEMOTE	lemtoe	lemfue	lemote	PERTAL	pretal	pbital	pertal
135	CRESKY	cersky	cipsky	cresky	SUMOTE	smuote	sniote	sumote
136	CLIGDOM	cilgdom	cefgdom	cligdom	KRALOM	karlom	koplom	kralom
137	DIRCEY	dricey	dpecey	dircey	SPORULE	soprule	safrule	sporule
138	TWENAGE	tewnage	tavnage	twenage	SURAM	sruam	sboam	suram
139	GLOPEN	golpen	gutpen	glopen	PRIOTZ	pirotz	pepotz	priotz
140	REMONE	remnoe	remvue	remone	WARKLE	wrakle	wpekle	warkle
141	DEASTLY	desatly	dezetly	deastly	TADER	tdaer	tbeer	tader
142	MIRATE	mriate	mpeate	mirate	MERTEL	mretel	mpatel	mertel
143	SOHOLE	soohle	soufle	sohole	WABEL	wbael	wdiel	wabel
144	SCOOF	socof	sugof	scoof	SALGE	slage	sfege	salge
145	DROCKET	dorcket	dupcket	drocket	BORPENT	bropent	bpupent	borpent
146	FLANCHY	flnachy	flmechy	flanchy	LOTZRER	ltozrer	lfuzrer	lotzrer
147	BANION	bainon	baemon	banion	JORSTEL	jrostel	jpustel	jorstel
148	TAMPY	tmapy	tnepy	tampy	NERGNIS	nregnis	nbagnis	nergnis
149	CRATH	crtah	crfeh	crath	KOLMACH	klomach	ktumach	kolmach
150	SULPENS	slupens	stopens	sulpens	HESTLER	hsetler	hzatler	hestler

Note. TL = transposed letter prime, control = orthographic control prime, repetition = repetition/identical prime. Underlining is used to illustrate the type of manipulation but was not shown during the experiment. Stimuli were taken from Türk and Domahs (in revision).

Table A3

English and German word and pseudoword stimuli of Experiment 3 on cross-modal TL priming

	English				German			
	Target	**TL**	**Control**	**PsH**	**Target**	**TL**	**Control**	**PsH**
				Non-identical cognates				
1	accent	ACNECT	ACMEGT	ACSCENT	Akzent	AKNEZT	AKMEST	AKTSENT
2	blouse	BSOULE	BZOUTE	BLOWSE	Bluse	BSULE	BZUTE	BLUHSE
3	class	CSALS	CZATS	KLASS	Klasse	KSALSE	KZATSE	CLASSE
4	flexible	FLEBIXLE	FLEDIVLE	FLEKSIBLE	flexibel	FLEBIXEL	FLEDIVEL	FLEKSIBEL
5	clinic	CNILIC	CMITIC	KLINIC	Klinik	KNILIK	KMITIK	CLINIK
6	correct	CORCERT	CORZEPT	CORRECKT	korrekt	KORKERT	KORFEPT	KORRECKT
7	crisis	CSIRIS	CZIBIS	CREISIS	Krise	KSIRE	KZIBE	KRIESE
8	direct	DICERT	DIGEPT	DIRECKT	direkt	DIKERT	DIFEPT	DIRECKT
9	effect	EFCEFT	EFGELT	EFFECKT	Effekt	EFKEFT	EFHELT	EFFECKT
10	exact	ECAXT	EGAVT	EKSACT	exakt	EKAXT	EHAVT	EKSAKT
11	flame	FMALE	FNATE	PHLAME	Flamme	FMALME	FNATME	PHLAMME
12	fresh	FSERH	FZEBH	PHRESH	frisch	FSIRCH	FZIBCH	PHRISCH
13	friend	FNIERD	FMIEPD	FREAND	Freund	FNEURD	FMEUPD	FRÄUND
14	palace	PACALE	PAGAFE	PALASE	Palast	PASALT	PAZAFT	PALASST
15	percent	PERNECT	PERMEGT	PERSCENT	Prozent	PRONEZT	PROMEST	PROTSENT
16	physics	PSYHICS	PZYBICS	PHISICS	Physik	PSYHIK	PZYBIK	PHÜSIK
17	concert	CONRECT	CONPEGT	CONSCERT	Konzert	KONREZT	KONPEST	KONTSERT
18	prince	PNIRCE	PMIPCE	PRINSE	Prinz	PNIRZ	PMIPZ	PRINTS
19	private	PVIRATE	PWIBATE	PREIVATE	privat	PVIRAT	PWIBAT	PRIVAHT
20	product	PDORUCT	PBOPUCT	PRODUCKT	Produkt	PDORUKT	PBOPUKT	PRODUCKT
21	project	PJORECT	PLOBECT	PROJECKT	Projekt	PJOREKT	PLOBEKT	PROJECKT
22	province	PVORINCE	PWOBINCE	PROVINSE	Provinz	PVORINZ	PWOBINZ	PROVINTS
23	record	REROCD	REPOGD	RECKORD	Rekord	REROKD	REPOHD	RECKORD
24	special	SCEPIAL	SGERIAL	SPESHIAL	speziell	SZEPIELL	SSEBIELL	SPETZIELL

25	stable	SBATLE	SDAFLE	STAIBLE	stabil	SBATIL	SDAFIL	STABIHL
26	process	PCORESS	PGOBESS	PROSCESS	Prozess	PZORESS	PSOBESS	PROTSESS
27	critical	CTIRICAL	CFIPICAL	CRUITICAL	kritisch	KTIRISCH	KFIPISCH	KRIETISCH
28	decade	DEDACE	DEBAGE	DECAIDE	Dekade	DEDAKE	DEBAHE	DEKAHDE
29	crystal	CSYRTAL	CZYPTAL	CRYSSTAL	Kristall	KSIRTALL	KZIPTALL	KRISSTALL
30	license	LINECSE	LIMEGSE	LISCENSE	Lizenz	LINEZZ	LIMESZ	LITSENZ
31	brother	BTORHER	BFOPHER	BRUTHER	Bruder	BDURER	BBUPER	BRUHDER
32	article	ARCITLE	ARGIFLE	ARTUICLE	Artikel	ARKITEL	ARHIFEL	ARTIHKEL
33	facade	FADACE	FABAGE	FASADE	Fassade	FASDASE	FASBAZE	FASADE
34	perfect	PERCEFT	PERGELT	PERFECKT	perfekt	PERKEFT	PERHELT	PERFECKT
35	plastic	PSALTIC	PZAFTIC	PLAZTIC	Plastik	PSALTIK	PZAFTIK	PLASSTIK
36	distance	DISNATCE	DISMALCE	DISTANSE	Distanz	DISNATZ	DISMALZ	DISTANTS
37	contact	CONCATT	CONGAFT	CONTACKT	Kontakt	KONKATT	KONHAFT	KONTACKT
38	lantern	LANRETN	LANPEFN	LANTARN	Laterne	LARETNE	LAPEFNE	LATÄRNE
39	spinach	SNIPACH	SMIBACH	SPINICH	Spinat	SNIPAT	SMIBAT	SPINAHT
40	crater	CTARER	CFAPER	CRAITER	Krater	KTARER	KFAPER	KRAATER
41	action	ATCION	ALGION	ACSHION	Aktion	ATKION	ALHION	AKZION
42	active	ATCIVE	AFGIVE	ACKTIVE	aktiv	ATKIV	AFHIV	ACKTIV
43	conflict	CONLFICT	CONTKICT	CONFLICKT	Konflikt	KONLFIKT	KONTKICT	KONFLICKT
44	concept	COCNEPT	COGMEPT	CONSEPT	Konzept	KOZNEPT	KOSMEPT	KONTSEPT
45	street	SRTEET	SPFEET	STREAT	Strasse	SRTAßE	SPFAßE	STRAHßE
46	central	CETNRAL	CEFMRAL	SENTRAL	zentral	ZETNRAL	ZEFMRAL	TSENTRAL
47	congress	COGNRESS	COCMRESS	CONGRASS	Kongress	KOGNRESS	KOCMRESS	KONGRÄSS
48	complex	COMLPEX	COMFREX	COMPLEKS	komplex	KOMLPEX	KOMFREX	KOMPLEKS
49	culture	CUTLURE	CUFKURE	COULTURE	Kultur	KUTLUR	KUFKUR	KULTUHR
50	complete	COMLPETE	COMFBETE	COMPLEATE	komplett	KOMLPETT	KOMFBETT	KOMPLÄTT
51	constant	COSNTANT	COZMTANT	KONSTANT	konstant	KOSNTANT	KOZMTANT	CONSTANT
52	extreme	EXRTEME	EXPLEME	EKSTREME	extrem	EXRTEM	EXPLEM	EKSTREM
53	factor	FATCOR	FALGOR	FACKTOR	Faktor	FATKOR	FALBOR	FACKTOR
54	garden	GADREN	GABPEN	GEARDEN	Garten	GATREN	GAFPEN	GAARTEN
55	hundred	HUDNRED	HUBMRED	HUNNDRED	Hundert	HUDNERT	HUBMERT	HUNNDERT

56	insect	ISNECT	IZMECT	INSECKT	Insekt	ISNEKT	IZMEKT	INSECKT
57	athlete	ATLHETE	ATFKETE	ATHLEETE	Athlet	ATLHET	ATFKET	ATHLEET
58	object	OJBECT	OLPECT	OBJECKT	Objekt	OJBEKT	OLPEKT	OBJECKT
59	respect	REPSECT	REBZECT	RESPECKT	Respekt	REPSEKT	REBZEKT	RESPECKT
60	scandal	SCADNAL	SCABMAL	SCANDLE	Skandal	SKADNAL	SKABMAL	SKANDAHL
61	silver	SIVLER	SIWTER	SILLVER	Silber	SIBLER	SIDTER	SILLBER
62	strike	SRTIKE	SPFIKE	STREIKE	Streik	SRTEIK	SPFEIK	STRAIK
63	temple	TEPMLE	TEBNLE	TAMPLE	Tempel	TEPMEL	TEBNEL	TÄMPEL
64	uncle	UCNLE	UGMLE	UNCKLE	Onkel	OKNEL	OFMEL	ONCKEL
65	wonder	WODNER	WOBMER	WONNDER	Wunder	WUDNER	WUBMER	WUNNDER
66	contrast	CONRTAST	CONPLAST	CONTRASST	Kontrast	KONRTAST	KONPLAST	KONTRASST
67	straw	SRTAW	SBLAW	STRAU	Stroh	SRTOH	SBLOH	STROOH
68	console	COSNOLE	COZMOLE	CONSOUL	Konsole	KOSNOLE	KOZMOLE	KONSOHLE
69	shrine	SRHINE	SPKINE	SHREINE	Schrein	SCRHEIN	SCPKEIN	SCHRAIN
70	address	ADRDESS	ADPBESS	ADDRASS	Adresse	ARDESSE	APBESSE	ADRÄSSE
71	shoulder	SHOUDLER	SHOUBFER	SHOULLDER	Schulter	SCHUTLER	SCHUHFER	SCHULLTER
72	school	SHCOOL	SKGOOL	SCHOUL	Schule	SHCULE	SKGULE	SCHUHLE
73	circus	CICRUS	CIGPUS	SIRCUS	Zirkus	ZIKRUS	ZIHPUS	TSIRKUS
74	instinct	INTSINCT	INLZINCT	INSTINCKT	Instinkt	INTSINKT	INLZINKT	INSTINCKT
75	bridge	BRIGDE	BRICBE	BRIGE	Brücke	BRÜKCE	BRÜHGE	BRÜKE
76	soldier	SODLIER	SOBTIER	SOALDIER	Soldat	SODLAT	SOBTAT	SOLDAHT
77	jacket	JAKCET	JAFGET	JACET	Jacke	JAKCE	JAFGE	JAKE
78	trumpet	TRUPMET	TRURNET	TROMPET	Trompete	TROPMETE	TRORNETE	TROMPEHTE
79	trophy	TROHPY	TROFBY	TROPHEE	Trophäe	TROHPÄE	TROFBÄE	TROPHEE
80	windy	WIDNY	WIBMY	WINNDY	windig	WIDNIG	WIBMIG	WINNDIG
81	canal	CNAAL	CMEAL	CANAUL	Kanal	KNAAL	KMEAL	KANAAL
82	cellar	CLELAR	CTALAR	CAELLER	Keller	KLELER	KTALER	KÄLLER
83	coffee	CFOFEE	CPEFEE	COFFY	Kaffee	KFAFEE	KPEFEE	KAFFEH
84	father	FTAHER	FLEHER	FOTHER	Vater	VTAER	VLEER	VAHTER
85	crown	CORWN	CUPWN	CROUN	Krone	KORNE	KUPNE	KROHNE
86	guitar	GUTIAR	GUFEAR	GUITTAR	Gitarre	GTIARRE	GFEARRE	GITTARRE

87	logic	LGOIC	LCUIC	LAGIC	Logik	LGOIK	LCUIK	LOHGIK
88	magic	MGAIC	MCEIC	MAGYC	Magie	MGAIE	MCEIE	MAGIH
89	focus	FCOUS	FGUUS	FOACUS	Fokus	FKOUS	FHUUS	FOHKUS
90	motive	MOITVE	MOELVE	MOATIVE	Motiv	MOITV	MOELV	MOTIEV
91	music	MSUIC	MZOIC	MEWSIC	Musik	MSUIK	MZOIK	MUSIEK
92	nature	NAUTRE	NAOFRE	NAITURE	Natur	NAUTR	NAOFR	NATUHR
93	ocean	OECAN	OAGAN	OSHEAN	Ozean	OEZAN	OASAN	OTSEAN
94	paper	PAEPR	PAABR	PAIPER	Papier	PAIPER	PAEBER	PAPIHR
95	mobile	MOIBLE	MOEDLE	MOABILE	mobil	MOIBL	MOEDL	MOBIHL
96	series	SEIRES	SEAPES	SEREES	Serie	SEIRE	SEAPE	SERJE
97	chemical	CHMEICAL	CHNAICAL	CHAMICAL	chemisch	CHMEISCH	CHNAISCH	CHEHMISCH
98	shame	SAHME	SEBME	SHAIME	Scham	SCAHM	SCEBM	SCHAHM
99	spear	SEPAR	SIRAR	SPIER	Speer	SEPER	SIRER	SPEHR
100	navel	NVAEL	NWEEL	NAIVAL	Nabel	NBAEL	NHEEL	NAHBEL
101	chamber	CHMABER	CHNEBER	TCHAMBER	Kammer	KMAMER	KNEMER	CHAMMER
102	group	GORUP	GUBUP	GROUPP	Gruppe	GURPPE	GOBPPE	GRUPE
103	jewel	JWEEL	JVAEL	JOUEL	Juwel	JWUEL	JVOEL	JUWEHL
104	weather	WETAHER	WEFEHER	WATHER	Wetter	WTETER	WFATER	WÄTTER
105	while	WHLIE	WHFEE	WHEILE	Weile	WELIE	WEFEE	WAILE
106	wagon	WGAON	WCEON	WAUGON	Wagen	WGAEN	WCEEN	WAHGEN
107	pepper	PPEPER	PBAPER	PEAPPER	Pfeffer	PFFEFER	PFHAFER	PFÄFFER
108	ghost	GHSOT	GHZUT	GHOAST	Geist	GESIT	GEZET	GAIST
109	machine	MACHNIE	MACHMEE	MACHIENE	Maschine	MASCHNIE	MASCHMEE	MASCHIENE
110	steel	SETEL	SAFEL	STIEL	Stahl	SATHL	SEFHL	STAAL
111	pirate	PRIATE	PBEATE	PEIRATE	Pirat	PRIAT	PBEAT	PIRAHT
112	cipher	CPIHER	CBEHER	SIPHER	Ziffer	ZFIFER	ZTEFER	TSIFFER
113	sugar	SGUAR	SCOAR	SHUGAR	Zucker	ZCUKER	ZGOKER	TSUCKER
114	needle	NEDELE	NEBALE	NEADLE	Nadel	NDAEL	NBEEL	NAHDEL
115	carrot	CRAROT	CPEROT	CAROT	Karotte	KRAOTTE	KPEOTTE	KARROTTE
116	coast	COSAT	COZET	CHOAST	Küste	KSÜTE	KZÖTE	CHÜSTE
117	shield	SHILED	SHITAD	SCIELD	Schild	SCHLID	SCHTED	SHILD

118	seven	SVEEN	SWAEN	SAEVEN	Sieben	SIBEEN	SIDAEN	SIHBEN
119	price	PIRCE	PEBCE	PREICE	Preis	PERIS	PIBIS	PRAIS
120	knuckle	KUNCKLE	KOMCKLE	NUCKLE	Knöchel	KÖNCHEL	KÜMCHEL	CNÖCHEL
Translation equivalent non-cognates								
1	future	FURUTE	FUSULE	FEWTURE	Zukunft	ZUNUKFT	ZUSULFT	TSUKUNFT
2	followed	FOLWOLED	FOLVOKED	FALLOWED	verfolgt	VERLOFGT	VERTOKGT	FERFOLGT
3	orchard	OHCRARD	OFCPARD	ORTCHARD	Obsthain	OTSBHAIN	OFSPHAIN	OBSTHEIN
4	cloth	CTOLH	CFOTH	KLOTH	Stoff	SFOTF	SLODF	SCHTOFF
5	docile	DOLICE	DOFIGE	DOSILE	folgsam	FOSGLAM	FOZGFAM	VOLGSAM
6	spider	SDIPER	SBIRER	SPEIDER	Spinne	SNIPNE	SMIRNE	SCHPINNE
7	intake	INKATE	INBALE	INTAIKE	Zufuhr	ZUHUFR	ZUBULR	TSUFUHR
8	inventor	INNEVTOR	INMEWTOR	INVANTOR	Erfinder	ERNIFDER	ERMIHDER	ÄRFINDER
9	enraged	ENGARED	ENCAPED	ENRAIGED	erzürnt	ERRÜZNT	ERPÜSNT	ÄRZÜRNT
10	twitchy	TWIHCTY	TWIBCFY	TWITCHEE	zappelig	ZAPLEPIG	ZAPTERIG	ZAPPELICH
11	benefit	BEFENIT	BELEMIT	BANEFIT	Gefallen	GELAFLEN	GETAKLEN	GEVALLEN
12	necklace	NECKCALE	NECKGATE	NECKLASE	Halsband	HALSNABD	HALSMAPD	HALLSBAND
13	parents	PANERTS	PAMEPTS	PERENTS	Eltern	ELRETN	ELPEFN	ÄLTERN
14	knocker	KCONKER	KGOMKER	NOCKER	Klopfer	KPOLFER	KBOTFER	CLOPFER
15	arrival	ARVIRAL	ARWIPAL	ARREIVAL	Ankunft	ANNUKFT	ANMUBFT	ANKUNVT
16	linkage	LINGAKE	LINCABE	LINKADGE	Gestänge	GESNÄTGE	GESMÄFGE	GESTENGE
17	annoyed	ANYONED	ANVOMED	ANNOIED	genervt	GERENVT	GEPEMVT	GENÄRVT
18	bracket	BCARKET	BGABKET	BRAKET	Klammer	KMALMER	KNATMER	CLAMMER
19	outcast	OUTSACT	OUTZAGT	OUTCAUST	geächtet	GEÄTHCET	GEÄLHGET	GEECHTET
20	brass	BSARS	BZAPS	BRAS	Blech	BCELH	BGEFH	BLÄCH
21	blotch	BTOLCH	BFOTCH	BLOCH	Klecks	KCELKS	KGETKS	KLÄCKS
22	carefree	CAFEREE	CATEBEE	CAREFRIE	sorglos	SOLGROS	SOTGBOS	SORGLOOS
23	prudence	PRUNEDCE	PRUMEBCE	PREWDENCE	Vorsicht	VORCISHT	VORGIZHT	FORSICHT
24	madness	MADSENS	MADZEMS	MADNES	Irrsinn	IRRNISN	IRRMIZN	IRSINN
25	chunk	CNUHK	CMUBK	TCHUNK	Klotz	KTOLZ	KFOTZ	KLOTS
26	betrayed	BETYARED	BETVAPED	BETRAIED	betrogen	BETGOREN	BETCOPEN	BETROHGEN
27	crevice	CVERICE	CWEBICE	CRAVICE	Spalte	SLAPTE	SFABTE	SCHPALTE

28	damage	DAGAME	DACANE	DAMADGE	Schaden	SCDAHEN	SCBAKEN	SCHAHDEN
29	delight	DEGILHT	DECIFHT	DELEIGHT	Genuss	GESUNS	GEZUMS	GENNUSS
30	durable	DUBARLE	DUDAPLE	DEWRABLE	haltbar	HABTLAR	HADTFAR	HALTBAHR
31	edible	EBIDLE	EHIKLE	ADIBLE	essbar	EBSSAR	EHSZAR	ESSBAHR
32	menace	MECANE	MEGAME	MENASE	Gefahr	GEHAFR	GEBALR	GEFAAR
33	failure	FAIRULE	FAIPUTE	FALURE	Ausfall	AUSLAFL	AUSTAKL	AUSVALL
34	farewell	FAWERELL	FAVEPELL	FAIRWELL	Lebewohl	LEWEBOHL	LEVEDOHL	LEHBEWOHL
35	foolish	FOOSILH	FOOZIFH	FOULISH	dämlich	DÄMCILH	DÄMGIFH	DÄHMLICH
36	nuisance	NUINASCE	NUIMAZCE	NUISANSE	Störung	STÖNURG	STÖMUPG	STÖHRUNG
37	message	MESGASE	MESCAZE	MEASSAGE	Meldung	MELNUDG	MELMUBG	MÄLDUNG
38	modest	MOSEDT	MOZEBT	MADEST	züchtig	ZÜTHCIG	ZÜFHGIG	TSÜCHTIG
39	pavement	PAMEVENT	PANEWENT	PAIVEMENT	Gehsteig	GETSHEIG	GELSKEIG	GEHSTAIG
40	scramble	SCMARBLE	SCNAPBLE	SCRAMBEL	Gerangel	GENARGEL	GEMAPGEL	GERRANGEL
41	window	WIDNOW	WIBMOW	WINDOA	Fenster	FESNTER	FEZMTER	FÄNSTER
42	harvest	HAVREST	HAWPEST	HEARVEST	Ertrag	ERRTAG	ERPHAG	ERTRAHG
43	pumpkin	PUPMKIN	PURNKIN	PAMPKIN	Kürbis	KÜBRIS	KÜPKIS	KÜRBISS
44	heedful	HEEFDUL	HEEHBUL	HEADFUL	achtsam	ACHSTAM	ACHZLAM	ACHTSAHM
45	monger	MOGNER	MOCMER	MANGER	Händler	HÄDNLER	HÄBMER	HENDLER
46	pocket	POKCET	POHGET	POCKIT	Tasche	TACSHE	TAGZHE	THASCHE
47	candle	CADNLE	CABMLE	CANDEL	Kerze	KEZRE	KESPE	KÄRZE
48	rampage	RAPMAGE	RARNAGE	RAMPAIGE	Randale	RADNALE	RABMALE	RANDAHLE
49	example	EXAPMLE	EXARNLE	EKSAMPLE	Beispiel	BEIPSIEL	BEIRZIEL	BAISPIEL
50	mistake	MITSAKE	MILZAKE	MISSTAKE	Fehler	FELHER	FETKER	FEELER
51	humble	HUBMLE	HUPNLE	HOMBEL	ärmlich	ÄRLMICH	ÄRTNICH	ERMLICH
52	template	TEPMLATE	TERNLATE	TEMPLAITE	Vorlage	VOLRAGE	VOTPAGE	FORLAGE
53	survey	SUVREY	SUWPEY	SURVAY	Umfrage	UMRFAGE	UMPHAGE	UMFRAHGE
54	increase	INRCEASE	INPGEASE	INCREESE	Mehrung	MERHUNG	MEPFUNG	MEERUNG
55	airplane	AIRLPANE	AIRTRANE	AIRPLAINE	Flugzeug	FLUZGEUG	FLUSCEUG	FLUGZÄUG
56	ambition	ABMITION	APNITION	AMBISHION	Ehrgeiz	ERHGEIZ	EPKGEIZ	EHRGEITS
57	moisture	MOITSURE	MOILZURE	MOYSTURE	Feuchte	FEUHCTE	FEUKGTE	FÄUCHTE
58	conduct	CODNUCT	COBMUCT	CONDUCKT	Betragen	BERTAGEN	BEPHAGEN	BETRAHGEN

59	latched	LACTHED	LAGLHED	LACHED	gesperrt	GEPSERRT	GERCERRT	GESPÄRRT
60	ingress	INRGESS	INPCESS	INGRASS	Eintritt	EITNRITT	EILMRITT	AINTRITT
61	cushion	CUHSION	CUKZION	CUTION	Polster	POSLTER	POZKTER	POLLSTER
62	descent	DECSENT	DEGZENT	DESENT	Abstieg	ABTSIEG	ABLZIEG	ABSTIHG
63	sickness	SICNKESS	SICMHESS	SIKNESS	Übelkeit	ÜBEKLEIT	ÜBEHTEIT	ÜBELKAIT
64	disgust	DIGSUST	DICZUST	DISSGUST	Abscheu	ABCSHEU	ABGZHEU	ABSCHÄU
65	dungeon	DUGNEON	DUCMEON	DUNDGEON	Verlies	VELRIES	VETPIES	FERLIES
66	invoked	IVNOKED	IWMOKED	INVOAKED	erfleht	EFRLEHT	EHPLEHT	ERFLEET
67	expense	EPXENSE	ERHENSE	EXPENCE	Unkosten	UKNOSTEN	UHMOSTEN	UNKOSSTEN
68	filthy	FILHTY	FILKLY	FILLTHY	dreckig	DREKCIG	DREHGIG	DRÄCKIG
69	bottle	BOTLTE	BOTHFE	BOTLE	Flasche	FLACSHE	FLAGZHE	PHLASCHE
70	laundry	LAUDNRY	LAUBMRY	LAWNDRY	Wäsche	WÄSHCE	WÄSFGE	WESCHE
71	fortress	FOTRRESS	FOLPRESS	PHORTRESS	Festung	FETSUNG	FELZUNG	FÄSTUNG
72	founder	FOUDNER	FOUBMER	FOWNDER	Gründer	GRÜDNER	GRÜBMER	GRÜNNDER
73	lecture	LETCURE	LEFGURE	LECTCHURE	Vortrag	VOTRRAG	VOLPRAG	FORTRAG
74	venture	VETNURE	VELMURE	VENTCHURE	Wagnis	WANGIS	WAMCIS	WAAGNIS
75	gambler	GABMLER	GADNLER	GALMBLER	Zocker	ZOKCER	ZOHGER	TSOCKER
76	kindred	KIDNRED	KIBMRED	KYNDRED	verwandt	VEWRANDT	VEVPANDT	FERWANDT
77	gentle	GETNLE	GEFMLE	JENTLE	sanft	SAFNT	SATMT	SANNFT
78	grumpy	GRUPMY	GRUBNY	GRUMPEE	grantig	GRATNIG	GRAFMIG	GRANTICH
79	hardship	HADRSHIP	HABPSHIP	HEARDSHIP	Notlage	NOLTAGE	NOHFAGE	NOOTLAGE
80	harlot	HALROT	HATPOT	HEARLOT	Dirne	DINRE	DIMPE	DIRRNE
81	giant	GINAT	GIMET	GEIANT	Riese	RISEE	RIZAE	RIHSE
82	desert	DSEERT	DZOERT	DESURT	Wüste	WSÜTE	WZÖTE	WÜHSTE
83	circle	CRICLE	CPUCLE	SIRCLE	Kreis	KERIS	KOPIS	KRAIS
84	dress	DERSS	DOPSS	DRASS	Kleid	KELID	KOTID	KLAID
85	cloud	COLUD	CUTUD	CLOWD	Wolke	WLOKE	WTUKE	WOLLKE
86	breadth	BERADTH	BAPADTH	BREDTH	Breite	BERITE	BAPITE	BRAITE
87	river	RVIER	RWAER	RIVVER	Fluss	FULSS	FOTSS	PHLUSS
88	bucket	BCUKET	BGOKET	BUKET	Eimer	EMIER	ENAER	AIMER
89	vessel	VSESEL	VZASEL	VEASSEL	Gefäß	GFEÄß	GHAÄß	GEFEß

90	virtue	VRITUE	VPATUE	VURTUE	Tugend	TGUEND	TCOEND	TUHGEND
91	command	CMOMAND	CNUMAND	COMAND	Befehl	BFEEHL	BHAEHL	BEFEEL
92	crayon	CARYON	CEPYON	CRAION	Kreide	KERIDE	KAPIDE	KRAIDE
93	basin	BSAIN	BZEIN	BAYSIN	Becken	BCEKEN	BGAKEN	BÄCKEN
94	polite	PLOITE	PTUITE	POLEITE	höflich	HFÖLICH	HLÜLICH	HÖHFLICH
95	fiber	FBIER	FDAER	FUIBER	Faser	FSAER	FZEER	FAHSER
96	supply	SPUPLY	SRUPLY	SUPPLUY	Vorrat	VRORAT	VPURAT	FORRAT
97	lonely	LNOELY	LMUELY	LOANLY	einsam	ENISAM	EMASAM	EINSAHM
98	broom	BOROM	BUPOM	BROUM	Besen	BSEEN	BZAEN	BEHSEN
99	proud	PORUD	PUBUD	PROWD	stolz	SOTLZ	SUFLZ	STOLTS
100	stage	SATGE	SELGE	STAIGE	Bühne	BHÜNE	BFÖNE	BÜNE
101	pillow	PLILOW	PTALOW	PILLOE	Kissen	KSISEN	KZASEN	KIßEN
102	sound	SONUD	SOMOD	SOWND	Klang	KLNAG	KLMEG	CLANG
103	tension	TNESION	TMASION	TENSHION	Spannung	SAPNNUNG	SERNNUNG	SCHPANNUNG
104	grief	GIREF	GAPEF	GREEF	Trauer	TARUER	TEPUER	THRAUER
105	funny	FNUNY	FMONY	FUNNEE	lustig	LSUTIG	LZOTIG	LUSTICH
106	device	DVEICE	DWAICE	DEVISE	Gerät	GREÄT	GPAÄT	GERET
107	driver	DIRVER	DABVER	DRYVER	Fahrer	FHARER	FTERER	VAHRER
108	frame	FARME	FEPME	FRAYME	Rahmen	RHAMEN	RFEMEN	RAAMEN
109	freedom	FEREDOM	FAPEDOM	FRIEDOM	Freiheit	FERIHEIT	FAPIHEIT	FRAIHEIT
110	guilt	GULIT	GUTAT	GUILLT	Schuld	SCUHLD	SCOFLD	SCHULT
111	wedding	WDEDING	WBADING	WEADDING	Hochzeit	HCOHZEIT	HGUHZEIT	HOCHZAIT
112	notion	NTOION	NLUION	NOSHION	Begriff	BGERIFF	BCARIFF	BEGRIF
113	opinion	OPNIION	OPMAION	OPUINION	Meinung	MENIUNG	MEMAUNG	MAINUNG
114	pattern	PTATERN	PLETERN	PATTURN	Muster	MSUTER	MZOTER	MUSSTER
115	border	BRODER	BPUDER	BOARDER	Grenze	GERNZE	GAPNZE	GRÄNZE
116	player	PALYER	PETYER	PLEIGHER	Spieler	SIPELER	SARELER	SPIHLER
117	prayer	PARYER	PEBYER	PREIGHER	Gebet	GBEET	GDAET	GEBEHT
118	dreadful	DERADFUL	DAPADFUL	DREDFULL	grausig	GARUSIG	GEPUSIG	GRAUSICH
119	review	RVEIEW	RWAIEW	REFIEW	Prüfung	PÜRFUNG	PÖBFUNG	PRÜHFUNG
120	traffic	TARFFIC	TEPFFIC	TRAFFICK	Verkehr	VREKEHR	VPAKEHR	FERKEHR

Pseudo-words								
1	cridge	CDIRGE	CLIBGE	KRIDGE	Knolem	KLONEM	KTOMEM	KNOLÄM
2	gnase	GSANE	GZAME	NASE	Pfunel	PNUFEL	PMUHEL	PFUHNEL
3	padult	PALUDT	PATUFT	PADDULT	Ralkwit	RAWKLIT	RAVKTIT	RALQUIT
4	glane	GNALE	GMATE	GLAINE	Brunte	BNURTE	BMOPTE	BRUNNTE
5	chosren	CSOHREN	CZOBREN	CHOASREN	Klente	KNELTE	KMEFTE	KLÄNTE
6	drublem	DLUBREM	DFUBPEM	DROBLEM	Truse	TSURE	TZUPE	TRUHSE
7	pollage	POLGALE	POLCATE	POLLADGE	Krunte	KTUNRE	KLUNBE	KRUNNTE
8	glanner	GNALNER	GMATNER	GLANNUR	Blino	BNILO	BMITO	BLIENO
9	hosert	HOREST	HOPEZT	HOZERT	Brölop	BLÖROP	BTÖBOP	BRÖLOPP
10	ropert	ROREPT	ROBEDT	ROAPERT	Brofel	BFOREL	BHOPEL	BROHFEL
11	stroley	SLROTEY	SKROFEY	STROWLEY	Brunfel	BFUNREL	BTUNPEL	BRUNNFEL
12	lomster	LOTSMER	LOFSNER	LOMBSTER	Grulte	GLURTE	GTUPTE	GRULLTE
13	clourish	CROULISH	CPOUTISH	CLAURISH	Frinke	FNIRKE	FMIPKE	FRINGKE
14	pratine	PTARINE	PFABINE	PRAUTINE	Glost	GSOLT	GZOFT	GLOSST
15	gliraine	GRILAINE	GBIFAINE	GLYRAINE	Gleipe	GPEILE	GREITE	GLAIPE
16	trumwot	TWUMROT	TMUMPOT	TRUMBWOT	Flaben	FBALEN	FDAFEN	FLAHBEN
17	atloms	ATMOLS	ATWOFS	ATLOMBS	Graten	GTAREN	GLABEN	GRAHTEN
18	ernlats	ERTLANS	ERFLAMS	IRNLATS	Trülich	TLÜRICH	TFÜBICH	TRÜHLICH
19	bronip	BNORIP	BMOBIP	BROUGHNIP	Pfeber	PBEFER	PDETER	PFEHBER
20	glinsep	GSINLEP	GZINTEP	GLINNSEP	Blete	BTELE	BFEJEN	BLEHTE
21	nashofs	NAFHOSS	NATHOZS	GNASHOFS	Klume	KMULE	KNUFE	KLUHME
22	densiped	DENPISED	DENBIZED	DENSIPPED	Spume	SMUPE	SNUBE	SPUHME
23	grothem	GTORHEN	GLOPHEN	GRAWTHEM	Tanore	TARONE	TAPOME	TANNORE
24	normstok	NOSMRTOK	NOZMPTOK	NORMSTOCK	Prume	PMURE	PNUBE	PRUHME
25	suitcast	SUITSACT	SUITZAGT	SOOTCAST	Klafe	KFALE	KPATE	KLAHFE
26	florty	FROLTY	FPOFTY	FLOARTY	Schrole	SCHLORE	SCHTOPE	SCHROHLE
27	tormest	TORSEMT	TORZENT	TOARMEST	Griele	GLIERE	GFIEBE	GRIHLE
28	crashine	CHASRINE	CKASPINE	KRASHINE	Bulase	BUSALE	BUZATE	BULAASE
29	prazy	PZARY	PSABY	PRASY	Spuwe	SWUPE	SVUFE	SPUHWE
30	mactate	MATTACE	MAFTAGE	MACTAITE	Klofe	KFOLE	KPOTE	KLOHFE

31	fringely	FNIRGELY	FMIPGELY	FRINDGELY	Grusen	GSUREN	GZUPEN	GRUHSEN
32	colstry	CORSTLY	COBSTFY	COALSTRY	Stohm	SHOTM	SFOLM	STOOM
33	fabtry	FARTBY	FAPTDY	FABTREE	Pragel	PGAREL	PCABEL	PRAHGEL
34	proncel	PNORCEL	PMOBCEL	PRONSEL	Schalper	SCLAHPER	SCFABPER	SCHALLPER
35	curfant	CURNAFT	CURMALT	CIRFANT	Kluper	KPULER	KRUFER	KLUHPER
36	blavet	BVALET	BWAKET	BLAVETT	Knaster	KSANTER	KZAMTER	KNASSTER
37	numpkit	NUKPMIT	NUFPNIT	NUMBKIT	Sturgel	SRUTGEL	SPUFGEL	SCHTURGEL
38	ragnure	RAGRUNE	RAGPUME	RAGNORE	Spurle	SRUPLE	SBUFLE	SCHPURLE
39	durfness	DUNFRESS	DUMFPESS	DIRFNESS	Trärchel	TRÄHCREL	TRÄFCPEL	TRERCHEL
40	kearless	KEARSELS	KEARZEFS	KEERLESS	Dorast	DOSART	DOZABT	DORASST
41	rantler	RATNLER	RALMLER	RANNTLER	Lasna	LANSA	LAMZA	LASSNA
42	fascor	FACSOR	FAGZOR	PHASCOR	Pristel	PRITSEL	PRILZEL	PRISSTEL
43	dopter	DOTPER	DAFBER	DAWPTOR	Kruspel	KRUPSEL	KRUBZEL	KRUSSPEL
44	ensine	ESNINE	EZMINE	ENCINE	Matlem	MALTEM	MAFHEM	MATTLEM
45	forner	FONRER	FOMBER	FOURNER	Sertau	SETRAU	SELPAU	SEHRTAU
46	garlep	GALREP	GATPEP	GARLEPP	Munke	MUKNE	MUFME	MUNGKE
47	ruptain	RUTPAIN	RULDAIN	RAPTAIN	Ralte	RATLE	RAFKE	RALLTE
48	bilming	BIMLING	BINTING	BILLMING	Fulpe	FUPLE	FUBTE	FULLPE
49	parlick	PALRICK	PATBICK	PARLIC	Nirle	NILRE	NIFPE	NIERLE
50	sindour	SIDNOUR	SIPMOUR	SINDOR	Stelke	STEKLE	STEHTE	STÄLKE
51	maltrow	MALRTOW	MALPFOW	MALTROE	Sampe	SAPME	SARNE	SAMMPE
52	nuster	NUTSER	NUFZER	NOSTER	Rapke	RAKPE	RAFBE	RAPPKE
53	carkot	CAKROT	CATBOT	CARCOT	Girbel	GIBREL	GIDPEL	GIERBEL
54	pigmure	PIMGURE	PINCURE	PIGMIRE	Gumpe	GUPME	GUBNE	GUMMPE
55	reflop	RELFOP	RETHOP	RIEFLOP	Lorte	LOTRE	LOFPE	LORRTE
56	pight	PIHGT	PIKCT	PEIGHT	Prompe	PROPME	PRORNE	PROMMPE
57	tinser	TISNER	TIZMER	TINCER	Narfe	NAFRE	NAKBE	NAHRFE
58	luntle	LUTNLE	LUFMLE	LONTLE	Marben	MABREN	MADPEN	MAHRBEN
59	nistle	NISLTE	NISFHE	KNISTLE	Rinse	RISNE	RIZME	RINNSE
60	thream	TRHEAM	TPFEAM	THREEM	Gampe	GAPME	GABNE	GAMMPE
61	palcuts	PACLUTS	PAGJUTS	PALCOTS	Fekte	FETKE	FELHE	FÄKTE

62	lumhon	LUHMON	LUFNON	LUMBHON	Tunge	TUGNE	TUCME	THUNGE
63	wadly	WALDY	WATBY	WAIDLY	Natze	NAZTE	NASLE	NATSE
64	absey	ASBEY	AZDEY	ABSEA	Gantel	GATNEL	GALMEL	GANNTEL
65	cletban	CLEBTAN	CLEPFAN	CLETTBAN	Lorke	LOKRE	LOFPE	LORCKE
66	trasler	TRALSER	TRAFZER	TRASSLER	Minke	MIKNE	MIFME	MINGKE
67	fietly	FIELTY	FIEFHY	FEETLY	Kanger	KAGNER	KACMER	CANGER
68	laption	LATPION	LALBION	LAPSHION	Morle	MOLRE	MOTBE	MOHRLE
69	pristion	PRITSION	PRILZION	PRISSTION	Laspel	LAPSEL	LABZEL	LASSPEL
70	salmort	SAMLORT	SANFORT	SALMART	Torgen	TOGREN	TOCBEN	THORGEN
71	towly	TOLWY	TOTVY	TOELY	Stipte	STITPE	STIFRE	STIPPTE
72	purper	PUPRER	PUDBER	PIRPER	Bletzor	BLEZTOR	BLESFOR	BLÄTZOR
73	londer	LODNER	LOBMER	LONDUR	Strule	SRTULE	SPLULE	STRUHLE
74	dunction	DUNTCION	DUNFCION	DUNCSHION	Pflaske	PFLAKSE	PFLAFZE	PFLASSKE
75	micture	MITCURE	MIFGURE	MICSHURE	Römsel	RÖSMEL	RÖZNEL	RÖHMSEL
76	pincel	PICNEL	PIGMEL	PINNCEL	Zursel	ZUSREL	ZUZPEL	TSURSEL
77	pentlet	PETNLET	PEMFLET	PENTELT	Kropsel	KROSPEL	KROZBEL	KROPPSEL
78	perneft	PENREFT	PEMPEFT	PERNIFT	Meutlung	MEULTUNG	MEUFHUNG	MÄUTLUNG
79	frotralt	FRORTALT	FROPLALT	FROUTRALT	Dreisnig	DREINSIG	DREIMZIG	DRAISNIG
80	prilness	PRINLESS	PRIMFESS	PRILLNESS	Pilmer	PIMLER	PINFER	PILLMER
81	houne	HONUE	HOMAE	HOWNE	Lauke	LAKUE	LALIE	LAUCKE
82	gurger	GRUGER	GBOGER	GIRGER	Maltor	MLATOR	MTETOR	MALLTOR
83	tinger	TNIGER	TMEGER	TINDGER	Katarp	KATRAP	KATBOP	CATARP
84	garty	GRATY	GPOTY	GARTEE	Marsile	MRASILE	MPUSILE	MARSIELE
85	toined	TONIED	TOMEED	TOYNED	Ramit	RMAIT	RNOIT	RAMIET
86	procean	PORCEAN	PUBCEAN	PROSCEAN	Mifas	MFIAS	MTEAS	MIEFAS
87	leamy	LEMAY	LENOY	LEEMY	Rokel	RKOEL	RHUEL	ROHKEL
88	lurdy	LRUDY	LPODY	LIRDY	Hömel	HMÖEL	HNÜEL	HÖHMEL
89	protoke	PORTOKE	PUPTOKE	PROTOAKE	Kutas	KTUAS	KFOAS	KUHTAS
90	cratch	CARTCH	CUBTCH	KRATCH	Mekis	MKEIS	MBAIS	MEHKIS
91	sneel	SENEL	SIMEL	SNEAL	Guper	GPUER	GBOER	GUHPER
92	tardon	TRADON	TPIDON	TARDEN	Wantnis	WNATNIS	WMUTNIS	WANDTNIS

93	grickle	GIRCKLE	GAPCKLE	GRICKEL	Lüteng	LTÜENG	LFÖENG	LÜHTENG
94	zippler	ZPIPLER	ZBEPLER	SIPPLER	Fetteln	FETTLEN	FETTKUN	FÄTTELN
95	norial	NOIRAL	NOEPAL	GNORIAL	Geite	GETIE	GEFEE	GAITE
96	dobot	DOOBT	DOAPT	DOUBOT	Binken	BNIKEN	BMEKEN	BINCKEN
97	pehearch	PEHERACH	PEHEBICH	PEHURCH	Kasen	KSAEN	KZEEN	KAHSEN
98	medember	MEDMEBER	MEDWIBER	MEDAMBER	Talzer	TLAZER	TFEZER	TALTZER
99	woobig	WOOIBG	WOOEPG	WOUBIG	Rangor	RNAGOR	RMIGOR	RANGOHR
100	seproach	SEPORACH	SEPUBACH	SEPROWCH	Hanzer	HNAZER	HMEZER	HANTSER
101	trobide	TROBDIE	TROBRAE	TROABIDE	Goden	GDOEN	GBUEN	GOHDEN
102	sabel	SBAEL	SREEL	SAYBEL	Runik	RNUIK	RMOIK	RUNICK
103	sirect	SIRCET	SIRGAT	SIRECKT	Mafte	MFATE	MLITE	MAFFTE
104	croject	CORJECT	CUBJECT	CROWJECT	Sirol	SRIOL	SPEOL	SIEROL
105	lemote	LEMTOE	LEMFUE	LEMATE	Pertal	PRETAL	PBITAL	PERTAHL
106	cresky	CERSKY	CIPSKY	CRESKEY	Sumote	SMUOTE	SNIOTE	SUMOHTE
107	dircey	DRICEY	DPECEY	DURCEY	Sporule	SOPRULE	SAFRULE	SPORUHLE
108	twenage	TEWNAGE	TAVNAGE	TWENADGE	Suram	SRUAM	SBOAM	SUHRAM
109	glopen	GOLPEN	GUTPEN	GLOAPEN	Priotz	PIROTZ	PEPOTZ	PRIOTS
110	remone	REMNOE	REMVUE	RIEMONE	Warkle	WRAKLE	WPEKLE	WARCKLE
111	deastly	DESATLY	DEZETLY	DEESTLY	Tader	TDAER	TBEER	TAHDER
112	mirate	MRIATE	MPEATE	MIRAYTE	Mertel	MRETEL	MPATEL	MÄRTEL
113	sohole	SOOHLE	SOUFLE	SOHOWLE	Wabel	WBAEL	WDIEL	WAHBEL
114	scoof	SOCOF	SUGOF	SCOUF	Salge	SLAGE	SFEGE	SALLGE
115	drocket	DORCKET	DUPCKET	DROCKIT	Borpent	BROPENT	BPUPENT	BOHRPENT
116	flanchy	FLNACHY	FLMECHY	FLANTCHY	Lotzrer	LTOZRER	LFUZRER	LOTSRER
117	banion	BAINON	BAEMON	BANNION	Jorstel	JROSTEL	JPUSTEL	JOHRSTEL
118	tampy	TMAPY	TNEPY	TEMPY	Nergnis	NREGNIS	NBAGNIS	NÄRGNIS
119	crath	CRTAH	CRFEH	CREATH	Kolmach	KLOMACH	KTUMACH	KOLLMACH
120	sulpens	SLUPENS	STOPENS	SULPENCE	Hestler	HSETLER	HZATLER	HÄSTLER

Note. TL = transposed letter prime, control = orthographic control prime, PsH = pseudohomophone prime. Underlining is used to illustrate the type of manipulation but was not shown during the experiment. Stimuli were taken from Türk and Domahs (in revision).

2. Appendix B – Full statistical report of all TF results

2.1 TF results of Experiment 1 on the role of orthography on auditory priming

TF power. Only results relevant for further analysis are reported. Analysis for the orthographic time window (400-500 ms) showed a main effect of condition ($W(2) = 112.329$, $p < .001$, $R^2 = 1.198\cdot10^{-3}$), frequency band ($W(4) = 2{,}996.486$, $p < .001$, $R^2 = 3.196\cdot10^{-2}$), anterior-posterior distribution ($W(2) = 200.588$, $p < .001$, $R^2 = 2.139\cdot10^{-3}$) and lateralization ($W(2) = 48.009$, $p < .001$, $R^2 = 5.120\cdot10^{-4}$). The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization was also marginally significant ($W(32) = 59.010$, $p = .064$, $R^2 = 6.410\cdot10^{-2}$).

Subsequent analyses per anterior-posterior distribution showed a main effect of condition ($W(2) = 110.630$, $p < .001$, $R^2 = 3.575\cdot10^{-3}$), frequency band ($W(4) = 1{,}131.873$, $p < .001$, $R^2 = 3.657\cdot10^{-2}$) and lateralization ($W(2) = 9.368$, $p = .009$, $R^2 = 3.027\cdot10^{-4}$) for the frontal ROI. The interactions between condition and frequency band ($W(2) = 404.518$, $p < .001$, $R^2 = 5.320\cdot10^{-2}$) and condition and lateralization ($W(2) = 128.361$, $p < .001$, $R^2 = 8.024\cdot10^{-3}$) were also significant. The three-way interaction between condition, frequency band and lateralization ($W(16) = 22.223$, $p = .136$) did not reach significance. The interaction with the highest significance was analyzed further, which was the interaction between condition and frequency band. In the delta band, TF power was higher for the O+P+ compared to the O-P+ condition ($z = 2.750$, $p = .012$, $d = 0.258$) and compared to the O-P- condition ($z = 8.655$, $p < .001$, $d = 0.811$). In the theta band, TF power was higher for the O+P+ compared to the O-P+ condition ($z = 4.559$, $p < .001$, $d = 0.263$) and compared to the O-P- condition ($z = 5.899$, $p < .001$, $d = 0.827$). In the alpha band, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.411$, $p = .032$, $d = 0.160$), but reduced compared to the O-P- condition ($z = -6.496$, $p < .001$, $d = 0.430$). In the beta band, the O+P+ condition showed higher TF power compared to the O-P+ condition (left: $z = 3.431$, $p = .001$, $d = 0.203$; midline: $z = 6.908$, $p < .001$, $d = 0.409$) and compared to the O-P- condition (left: $z = 4.115$, $p < .001$, $d = 0.244$; midline: $z = 3.130$, $p = .004$, $d = 0.185$) at left and midline electrode sites. At right electrode sites, power was higher for the O+P+ compared to the O-P+ condition ($z = 8.713$, $p < .001$, $d = 0.516$), but reduced compared to the O-P- condition ($z = -3.090$, $p = .004$, $d = 0.183$). In the gamma band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -2.137$, $p = .038$, $d = 0.076$) at left electrode sites, but no difference was found at midline ($z < 1$, $p = .662$) and right ($z = -1.213$, $p = .451$) electrode sites. Power was also lower for the O+P+ compared to the O-P- condition (left: $z = -2.137$, $p = .065$, $d = 0.069$; midline: $z = -4.705$, $p < .001$, $d = 0.153$; right: $z = -13.058$,

$p < .001$, $d = 0.424$). This effect was strongest at right electrode sites and weaker at midline and left electrode sites.

For the central ROI, main effects of condition ($W(2) = 16.269$, $p < .001$, $R^2 = 5.013 \cdot 10^{-4}$), frequency band ($W(4) = 1{,}542.052$, $p < .001$, $R^2 = 4.751 \cdot 10^{-2}$) and lateralization ($W(2) = 93.035$, $p < .001$, $R^2 = 2.867 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 43.501$, $p < .001$, $R^2 = 6.871 \cdot 10^{-2}$) also reached significance. At left lateralized electrode sites, power was higher for the O+P+ compared to the O-P- condition ($z = 4.005$, $p < .001$, $d = 0.650$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, power was marginally higher for the O+P+ compared to the O-P+ condition ($z = 1.967$, $p = .098$, $d = 0.261$), but no difference was found between the O+P+ and the O-P- condition ($z < 1$, $p = 1.000$). In the alpha band, power was reduced for the O+P+ condition compared to the O-P- condition ($z = -5.199$, $p < .001$, $d = 0.596$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, power was slightly reduced for the O+P+ compared to the O-P- condition ($z = -2.068$, $p = .077$, $d = 0.123$). No difference was found for the O+P+ compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the gamma band, TF power was reduced for the O+P+ condition compared to the O-P+ condition ($z = -12.425$, $p < .001$, $d = 0.403$) and compared to the O-P- condition ($z = -4.944$, $p < .001$, $d = 0.160$). At midline electrodes, power was higher for the O+P+ condition compared to the O-P- condition ($z = 4.376$, $p < .001$, $d = 0.710$), but not compared to the O-P+ condition ($z = 1.381$, $p = .334$) in the delta band. In the theta band, no effect of condition was found ($W(2) = 1.074$, $p = .585$). In the alpha band, power was reduced for the O+P+ compared to the O-P- condition ($z = -6.784$, $p < .001$, $d = 0.778$), but no difference was found between the O+P+ and the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, power was higher for the O+P+ compared to the O-P+ condition ($z = 5.408$, $p < .001$, $d = 0.320$), but not compared to the O-P- condition ($z = -1.062$, $p = 0.577$). In the gamma band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -4.477$, $p < .001$, $d = 0.145$) and marginally reduced compared to the O-P- condition ($z = -1.963$, $p = .099$, $d = 0.064$). At right lateralized electrode sites, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.847$, $p = .009$, $d = 0.462$) and compared to the O-P- condition ($z = 5.382$, $p < .001$, $d = 0.873$) in the delta band. In the theta band, power was higher for the O+P+ compared to the O-P+ condition ($z = 3.244$, $p = .002$, $d = 0.430$), but not compared to the O-P- condition ($z < 1$, $p = .678$). In the alpha band, power was reduced for the O+P+ compared to the O-P- condition ($z = -5.978$, $p < .001$, $d = 0.686$), but not for the O+P+ compared to the O-P+ condition ($z = 1.423$, $p = .309$). In the beta band, power was reduced for the O+P+ compared to the O-P- condition ($z = -2.748$, $p = .012$, $d = 0.163$), but not for the O+P+ compared to the O-P+ condition ($z = 1.840$, $p = .132$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 5.653$, $p < .001$, $d = 0.183$) and compared to the O-P- condition ($z = 3.642$, $p < .001$, $d = 0.118$).

For the parietal ROI, main effects of condition ($W(2) = 131.995$, $p < .001$, $R^2 = 4.136 \cdot 10^{-3}$), frequency band ($W(4) = 891.045$, $p < .001$, $R^2 = 2.792 \cdot 10^{-2}$) and of lateralization ($W(2) = 17.186$, $p < .001$, $R^2 = 5.385 \cdot 10^{-4}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 23.870$, $p = .092$, $R^2 = 5.655 \cdot 10^{-2}$) was marginally significant. At left lateralized electrode sites, power was higher in the O+P+ compared to the O-P+ condition ($z = 2.113$, $p = .069$, $d = 0.343$) and compared to the O-P- condition ($z = 6.739$, $p < .001$, $d = 1.093$) in the delta band. In the theta band, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.508$, $p = .024$, $d = 0.332$), but not compared to the O-P- condition ($z < 1$, $p = .694$). In the alpha band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -4.561$, $p < .001$, $d = 0.523$) and compared to the O-P- condition ($z = -8.655$, $p < .001$, $d = 0.993$). In the beta band, power was reduced for the O+P+ compared to the O-P- condition ($z = -4.011$, $p < .001$, $d = 0.238$), but not compared to the O-P+ condition ($z < 1$, $p = .999$). In the gamma band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -13.113$, $p < .001$, $d = 0.425$) and compared to the O-P- condition ($z = -3.224$, $p = .003$, $d = 0.105$). At midline electrodes, power was higher for the O+P+ condition compared to the O-P+ condition ($z = 2.559$, $p = .022$, $d = 0.413$) and compared to the O-P- condition ($z = 6.744$, $p < .001$, $d = 1.094$) in the delta band. In the theta band, power was higher for the O+P+ condition compared to the O-P+ condition ($z = 2.524$, $p = .023$, $d = 0.334$), but not compared to the O-P- condition ($z = 1.680$, $p = .186$). In the alpha band, power was slightly reduced for the O+P+ compared to the O-P+ condition ($z = -2.011$, $p = .089$, $d = 0.231$) and reduced compared to the O-P- condition ($z = -7.782$, $p < .001$, $d = 0.893$). In the beta band, power was lower for the O+P+ compared to the O-P- condition ($z = -6.306$, $p < .001$, $d = 0.374$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the gamma band, power was lower for the O+P+ compared to the O-P+ condition ($z = -10.061$, $p < .001$, $d = 0.326$) and compared to the O-P- condition ($z = -3.801$, $p < .001$, $d = 0.123$). At right electrode sites, power was higher for the O+P+ condition compared to the O-P+ condition ($z = 4.029$, $p < .001$, $d = 0.654$) and compared to the O-P- condition ($z = 6.267$, $p < .001$, $d = 1.017$) in the delta band. In the theta band, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.885$, $p = .008$, $d = 0.382$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the alpha band, power was marginally reduced for the O+P+ compared to the O-P+ condition ($z = -1.999$, $p = .091$, $d = 0.229$) and reduced compared to the O-P- condition ($z = -8.281$, $p < .001$, $d = 0.950$). In the beta band, power was reduced for the O+P+ condition compared to the O-P- condition ($z = -6.846$, $p < .001$, $d = 0.406$), but not compared to the O-P+ condition ($z = -1.322$, $p = .372$). In the gamma band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -6.440$, $p < .001$, $d = 0.209$) and compared to the O-P- condition ($z = -3.217$, $p = .003$, $d = 0.104$).

For the phonological time window, a main effect of condition ($W(2) = 359.674$, $p < .001$, $R^2 = 3.550 \cdot 10^{-3}$), of frequency band ($W(4) = 5{,}576.546$, $p < .001$, $R^2 = 5.504 \cdot 10^{-2}$), of anterior-posterior distribution ($W(2) = 322.396$, $p < .001$, $R^2 = 3.182 \cdot 10^{-3}$) and of lateralization ($W(2) = 114.598$, $p < .001$, $R^2 = 1.131 \cdot 10^{-3}$) were found. The three-way interactions between condition, frequency band and anterior distribution ($W(16) = 240.664$, $p < .001$, $R^2 = 8.267 \cdot 10^{-2}$), and between condition, anterior-posterior distribution and lateralization ($W(8) = 80.459$, $p < .001$, $R^2 = 1.118 \cdot 10^{-2}$) were also significant. The interaction between condition, frequency band and lateralization ($W(2) = 23.821$, $p = .094$, $R^2 = 7.360 \cdot 10^{-2}$) was marginally significant. The four-way interaction did not reach significance ($W(32) = 27.524$, $p = .693$). The three-way interaction with the highest significance was analyzed further which was the interaction between condition, frequency band and anterior-posterior distribution.

Subsequent analyses per anterior-posterior distribution showed main effects of condition ($W(2) = 187.982$, $p < .001$, $R^2 = 5.517 \cdot 10^{-3}$), frequency band ($W(4) = 2{,}165.897$, $p < .001$, $R^2 = 6.356 \cdot 10^{-2}$) and lateralization ($W(2) = 17.049$, $p < .001$, $R^2 = 5.003 \cdot 10^{-4}$) at frontal electrode sites. The two-way interactions between condition and frequency band ($W(8) = 329.860$, $p < .001$, $R^2 = 7.873 \cdot 10^{-2}$) and condition and lateralization ($W(4) = 69.960$, $p < .001$, $R^2 = 8.069 \cdot 10^{-3}$) were also significant. The three-way interaction between condition, frequency band and lateralization ($W(16) = 8.369$, $p = .937$) did not reach significance. The interaction with the highest significance was analyzed further which was the interaction between condition and frequency band. In the delta band, power was reduced for the O-P- compared to the O-P+ ($z = -4.780$, $p < .001$, $d = 0.448$) and compared to the O+P+ conditions ($z = -6.942$, $p < .001$, $d = 0.650$). In the theta band, no effect of condition ($W(2) = 2.805$, $p = .246$) and no interaction between condition and lateralization ($W(4) = 5.301$, $p = .258$) were found. In the alpha band, power was higher for the O-P- compared to the O-P+ condition ($z = 9.974$, $p < .001$, $d = 0.661$) and compared to the O+P+ condition ($z = 10.910$, $p < .001$, $d = 0.723$). In the beta band, power was reduced for the O-P- compared to the O+P+ condition ($z = -3.250$, $p = .002$, $d = 0.193$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) at left electrode sites. At midline sites, power was higher for the O-P- compared to the O-P+ condition ($z = 3.841$, $p < .001$, $d = 0.228$), but not compared to the O+P+ condition ($z = 1.425$, $p = .308$). At right electrode sites, power was higher for the O-P- condition compared to the O-P+ condition ($z = 6.588$, $p < .001$, $d =$

0.390), but not compared to the O+P+ condition ($z < 1$, $p = .754$). In the gamma band, power was higher for the O-P- compared to the O-P+ condition ($z = 2.155$, $p = .062$, $d = 0.070$) and compared to the O+P+ condition ($z = 4.017$, $p < .001$, $d = 0.130$) at left electrode positions. At midline electrode positions, power was higher for the O-P- compared to the O-P+ condition ($z = 8.930$, $p < .001$, $d = 0.290$) and compared to the O+P+ condition ($z = 8.140$, $p < .001$, $d = 0.264$). At right electrode sites, power was higher for the O-P- compared to the O-P+ condition ($z = 13.295$, $p < .001$, $d = 0.431$) and compared to the O+P+ condition ($z = 12.961$, $p < .001$, $d = 0.421$).

In the central ROI, main effects of condition ($W(2) = 111.607$, $p < .001$, $R^2 = 3.166 \cdot 10^{-3}$), frequency band ($W(4) = 2{,}713.081$, $p < .001$, $R^2 = 7.695 \cdot 10^{-2}$) and lateralization ($W(2) = 141.429$, $p < .001$, $R^2 = 4.011 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 24.688$, $p = .076$, $R^2 = 9.820 \cdot 10^{-2}$) was marginally significant. At left lateralized electrodes, power was lower for the O-P- compared to the O-P+ condition ($z = -2.818$, $p = .010$, $d = 0.457$) and compared to the O+P+ condition ($z = -2.623$, $p = .017$, $d = 0.426$) in the delta band. In the theta band, power was higher for the O-P- compared to the O+P+ condition ($z = 2.697$, $p = .014$, $d = 0.357$), but not compared to the O-P+ condition ($z = 1.941$, $p = .104$). In the alpha band, power was higher for the O-P- compared to the O-P+ ($z = 5.905$, $p < .001$, $d = 0.677$) and compared to the O+P+ condition ($z = 6.964$, $p < .001$, $d = 0.799$). In the beta band, power was higher for the O-P- compared to the O-P+ condition ($z = 4.746$, $p < .001$, $d = 0.281$) and compared to the O+P+ condition ($z = 4.091$, $p < .001$, $d = 0.242$). In the gamma band, power was higher for the O-P- compared to the O+P+ condition ($z = 8.160$, $p < .001$, $d = 0.265$), but no effect was found compared to the O-P+ condition ($z = 1.685$, $p = .184$). At midline electrode sites, power was reduced for the O-P- compared to the O+P+ condition ($z = -3.025$, $p = .005$, $d = 0.491$), but not compared to the O-P+ condition ($z = -1.874$, $p = .122$) in the delta band. In the theta band, no effect of condition was found ($W(2) = 3.352$, $p = .187$). In the alpha band, power was higher for the O-P- condition compared to the O-P+ condition ($z = 7.980$, $p < .001$, $d = 0.915$) and compared to the O+P+ condition ($z = 9.398$, $p < .001$, $d = 1.078$). In the beta band, power was higher for the O-P- compared to the O-P+ condition ($z = 7.874$, $p < .001$, $d = 0.466$) and higher compared to the O+P+ condition ($z = 4.767$, $p < .001$, $d = 0.282$). In the gamma band, power was higher for the O-P- compared to the O+P+ condition ($z = 3.905$, $p < .001$, $d = 0.127$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). At right electrode sites, power was reduced for the O-P- compared to the O+P+ condition ($z = -4.612$, $p < .001$, $d = 0.748$), but not compared to the O-P+ condition ($z = -1.948$, $p = .103$) in the delta band. In the theta band, power was higher for the O-P- compared to the

O-P+ condition ($z = -2.192$, $p = .057$, $d = 0.290$) but not compared to the O+P+ condition ($z < 1$, $p = 1.000$). In the alpha band, power was higher for the O-P- compared to the O-P+ condition ($z = 8.142$, $p < .001$, $d = 0.934$) and higher compared to the O+P+ condition ($z = 6.758$, $p < .001$, $d = 0.775$). In the beta band, power was higher for the O-P- condition compared to the O-P+ condition ($z = 6.844$, $p < .001$, $d = 0.405$) and compared to the O+P+ condition ($z = 4.356$, $p < .001$, $d = 0.258$). In the gamma band, no difference was found for the O-P- compared to the O-P+ ($z = 1.101$, $p = .542$) nor compared to the O+P+ condition ($z = -1.078$, $p = .562$).

In the parietal ROI, main effects of condition ($W(2) = 164.180$, $p < .001$, $R^2 = 4.800 \cdot 10^{-3}$), frequency band ($W(4) = 1{,}490.600$, $p < .001$, $R^2 = 4.357 \cdot 10^{-2}$) and lateralization ($W(2) = 25.098$, $p < .001$, $R^2 = 7.336 \cdot 10^{-4}$) were found. The interactions between condition and frequency band ($W(8) = 731.881$, $p < .001$, $R^2 = 6.974 \cdot 10^{-2}$) and condition and lateralization ($W(4) = 22.888$, $p < .001$, $R^2 = 6.200 \cdot 10^{-3}$) also reached significance. The three-way interaction between condition, frequency band and lateralization ($W(16) = 20.096$, $p = .216$) was not significant. The two-way interaction with the highest significance was analyzed further, which was the interaction between condition and frequency band. In the delta band, power was reduced for the O-P- compared to the O-P+ ($z = -5.546$, $p < .001$, $d = 0.519$) and compared to the O+P+ conditions ($z = -9.430$, $p < .001$, $d = 0.883$). No effect of condition ($W(2) = 3.383$, $p = .184$) nor an interaction between condition and lateralization ($W(3) < 1$, $p = .912$) were found in the theta band. In the alpha band, power was higher for the O-P- compared to the O-P+ ($z = 7.981$, $p < .001$, $d = 0.529$) and compared to the O+P+ condition ($z = 12.040$, $p < .001$, $d = 0.797$). In the beta band, power was higher for the O-P- compared to the O-P+ ($z = 18.070$, $p < .001$, $d = 0.618$) and compared to the O+P+ condition ($z = 13.736$, $p < .001$, $d = 0.470$). In the gamma band, power was reduced for the O-P- compared to the O-P+ condition ($z = -9.650$, $p < .001$, $d = 0.181$), but higher compared to the O+P+ condition ($z = 8.710$, $p < .001$, $d = 0.163$). The difference between O-P- and O-P+ was strongest at left electrode sites (left: $z = -8.250$, $p < .001$, $d = 0.268$; midline: $z = -5.875$, $p < .001$, $d = 0.191$; right: $z = -2.223$, $p = .053$, $d = 0.072$), while the difference between O-P- and O+P+ was strongest at midline and right electrode sites (left: $z = 4.510$, $p < .001$, $d = 0.146$; midline: $z = 5.747$, $p < .001$, $d = 0.186$; right: $z = 5.114$, $p < .001$, $d = 0.166$).

ITPC. For the orthographic time window, main effects of condition ($W(2) = 754.214$, $p < .001$, $R^2 = 9.476 \cdot 10^{-3}$), frequency band ($W(4) = 28.033$, $p < .001$, $R^2 = 3.522 \cdot 10^{-4}$), anterior-posterior distribution ($W(2) = 10.920$, $p = .004$, $R^2 = 1.372 \cdot 10^{-4}$) and lateralization ($W(2) = 8.090$, $p = .018$, $R^2 = 1.016 \cdot 10^{-4}$) were found. The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization ($W(32) = 68.607$, $p < .001$, $R^2 = 1.922 \cdot 10^{-2}$) also reached significance.

For frontal electrode sites, main effects of condition ($W(2) = 384.953$, $p < .001$, $R^2 = 1.429 \cdot 10^{-2}$), frequency band ($W(4) = 38.470$, $p < .001$, $R^2 = 1.428 \cdot 10^{-3}$) and lateralization ($W(2) = 47.857$, $p < .001$, $R^2 = 1.777 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 41.090$, $p < .001$, $R^2 = 2.753 \cdot 10^{-2}$) was significant. At left electrodes, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 2.258$, $p = .048$, $d = 0.366$), but not compared to the O-P- condition ($z = 1.662$, $p = .193$) in the delta band. In the theta band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 2.296$, $p = .043$, $d = 0.304$), but not compared to the O-P- condition ($z = 1.035$, $p = .602$). In the alpha band, ITPC was higher for the O+P+ compared to the O-P+ ($z = 4.029$, $p < .001$, $d = 0.462$), but not compared to the O-P- condition ($z = 1.797$, $p = .145$). In the beta band, ITPC in the O+P+ condition was higher compared to the O-P+ ($z = 11.745$, $p < .001$, $d = 0.696$) and compared to the O-P- condition ($z = 7.776$, $p < .001$, $d = 0.461$). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 7.116$, $p < .001$, $d = 0.231$), but lower compared to the O-P- condition ($z = -4.145$, $p < .001$, $d = 0.134$). At midline electrode positions, no effect of condition ($W(2) = 4.524$, $p = .104$) was found in the delta band nor in the theta band ($W(2) = 2.472$, $p = .291$). In the alpha band, ITPC was slightly higher for the O+P+ compared to the O-P+ condition ($z = 2.118$, $p = .068$, $d = 0.243$), but not compared to the O-P- condition ($z = 1.646$, $p = .199$). In the beta band, ITPC was higher for the O+P+ compared to the O-P+ ($z = 10.699$, $p < .001$, $d = 0.634$) and compared to the O-P- condition ($z = 7.458$, $p < .001$, $d = 0.442$). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 7.004$, $p < .001$, $d = 0.679$), but not compared to the O-P- condition ($z = 1.670$, $p = .190$). At the right electrode sites, no effect of condition was found in the delta band ($W(2) = 4.262$, $p = .119$). In the theta band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 3.227$, $p = .003$, $d = 0.428$) and compared to the O-P- condition ($z = 2.541$, $p = .022$, $d = 0.337$). In the alpha band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 3.048$, $p = .005$, $d = 0.350$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the beta band, ITPC was higher in the O+P+ condition compared to the O-P+ ($z = 5.543$, $p < .001$, $d = 0.328$) and compared to the O-P- condition ($z = 6.510$, $p < .001$, $d = 0.386$). In the gamma band, ITPC was higher for the O+P+ condition compared to the O-P+ condition ($z = 7.235$, $p < .001$, $d = 0.235$) and compared to the O-P- condition ($z = 3.777$, $p < .001$, $d = 0.123$).

At central electrode sites, main effects of condition (*W*(2) = 280.482, $p < .001$, $R^2 = 1.052 \cdot 10^{-2}$), frequency band (*W*(4) = 49.687, $p < .001$, $R^2 = 1.863 \cdot 10^{-3}$) and lateralization (*W*(2) = 9.951, $p = .007$, $R^2 = 3.732 \cdot 10^{-4}$) were found. The three-way interaction between condition, frequency band and lateralization (*W*(16) = 47.742, $p < .001$, $R^2 = 1.768 \cdot 10^{-2}$) also reached significance. At left electrode positions, no effect of condition was found in the delta band (*W*(2) = 3.200, $p = .202$). In the theta band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 3.298$, $p = .002$, $d = 0.437$), but not compared to the O-P- condition ($z = -1.407$, $p = .319$). In the alpha band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 2.713$, $p = .013$, $d = 0.311$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the beta band, ITPC in the O+P+ condition was higher compared to the O-P+ condition ($z = 7.485$, $p < .001$, $d = 0.443$) and compared to the O-P- condition ($z = 5.225$, $p < .001$, $d = 0.309$). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 7.902$, $p < .001$, $d = 0.256$), but not compared to the O-P- condition ($z = -1.460$, $p = .288$). At midline electrode sites, no effect of condition (*W*(2) = 1.863, $p = .394$) was found in the delta band. In the theta band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 2.644$, $p = .016$, $d = 0.350$), but not compared to the O-P- condition ($z = 1.035$, $p = .602$). In the alpha band, no effect of condition (*W*(2) < 1, $p = .746$) was found. In the beta band, ITPC was higher for the O+P+ compared to the O-P+ ($z = 6.665$, $p < .001$, $d = 0.395$) and compared to the O-P- condition ($z = 4.612$, $p < .001$, $d = 0.273$). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 7.707$, $p = .001$, $d = 0.250$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). At right electrode positions, no effect of condition (*W*(2) = 2.567, $p = .277$) was found in the delta band, in the theta band (*W*(2) = 1.358, $p = .507$) nor in the alpha band (*W*(2) = 3.896, $p = .143$). In the beta band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 4.379$, $p < .001$, $d = 0.259$), but not compared to the O-P- condition ($z = 1.925$, $p = .108$). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition ($z = 6.671$, $p < .001$, $d = 0.216$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$).

At parietal electrode sites, main effects of condition (*W*(2) = 144.120, $p < .001$, $R^2 = 5.465 \cdot 10^{-3}$), frequency band (*W*(4) = 17.666, $p = .001$, $R^2 = 6.698 \cdot 10^{-4}$) and lateralization (*W*(2) = 14.326, $p < .001$, $R^2 = 5.432 \cdot 10^{-4}$) were found. The three-way interaction between condition, frequency band and lateralization (*W*(16) = 33.061, $p = .007$, $R^2 = 1.258 \cdot 10^{-2}$) was also significant. At left electrode sites, no effect of condition was found in the delta band (*W*(2) < 1, $p = .733$). In the theta band, higher ITPC for the O+P+ compared to the O-P+ condition ($z = 3.153$, $p = .003$, $d = 0.418$) was found. No difference in ITPC was found for the

O+P+ compared to the O-P- condition (*z* < 1, *p* = .821). No effect of condition was found in the alpha band (*W*(2) = 2.581, *p* = .275) nor in the beta band (*W*(2) = 1.103, *p* = .576). In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition (*z* = 9.820, *p* < .001, *d* = 0.319), but not compared to the O-P- condition (*z* < 1, *p* = 1.000). At midline electrode sites, no effect of condition was found in the delta band (*W*(2) = 4.574, *p* = .102), nor in the theta band (*W*(2) = 3.647, *p* = .162). In the alpha band, ITPC was marginally lower for the O+P+ compared to the O-P- condition (*z* = -2.037, *p* = .083, *d* = 0.234), but no difference was found compared to the O-P+ condition (*z* < 1, *p* = 1.000). In the beta band, no effect of condition (*W*(2) = 2.961, *p* = .228) was found. In the gamma band, ITPC was higher for the O+P+ condition compared to the O-P+ condition (*z* = 8.277, *p* < .001, *d* = 0.269), but not compared to the O-P- condition (*z* = 1.044, *p* = .593). At right electrode sites, ITPC was lower for the O+P+ compared to the O-P- condition (*z* = -2.284, *p* = .045, *d* = 0.371), but not compared to the O-P+ condition (*z* = -1.821, *p* = .137) in the delta band. In the theta band, no effect of condition (*W*(2) = 1.954, *p* = .377) was found. In the alpha band, ITPC was lower for the O+P+ compared to the O-P+ condition (*z* = -2.372, *p* = .035, *d* = 0.272) and compared to the O-P- condition (*z* = -3.241, *p* = .002, *d* = 0.372). In the beta band, no effect of condition (*W*(2) = 3.731, *p* = .155) was found. In the gamma band, ITPC was higher for the O+P+ compared to the O-P+ condition (*z* = 6.443, *p* < .001, *d* = 0.209) and compared to the O-P+ condition (*z* = 2.943, *p* = .007, *d* = 0.096).

For the phonological time window, a main effect of condition (*W*(2) = 322.969, *p* < .001, $R^2 = 4.087 \cdot 10^{-3}$), frequency band (*W*(4) = 78.047, *p* < .001, $R^2 = 9.877 \cdot 10^{-4}$), anterior-posterior distribution (*W*(2) = 22.912, *p* < .001, $R^2 = 2.900 \cdot 10^{-4}$) and lateralization (*W*(2) = 13.663, *p* = .001, $R^2 = 1.729 \cdot 10^{-4}$) were found. The four-way interaction also showed significance (*W*(32) = 96.791, *p* < .001, $R^2 = 1.878 \cdot 10^{-2}$).

At frontal electrode positions, main effects of condition (*W*(2) = 218.041, *p* < .001, $R^2 = 8.087 \cdot 10^{-3}$), frequency band (*W*(4) = 47.300, *p* < .001, $R^2 = 1.754 \cdot 10^{-3}$) and lateralization (*W*(2) = 20.370, *p* < .001, $R^2 = 7.556 \cdot 10^{-4}$) were found. The three-way interaction (*W*(16) = 43.565, *p* < .001, $R^2 = 2.299 \cdot 10^{-2}$) was also significant. At left electrode sites, no effect of condition (*W*(2) = 4.014, *p* = .134) was found in the delta band. In the theta band, ITPC was higher for the O-P- condition compared to the O-P+ condition (*z* = 3.079, *p* = .004, *d* = 0.408), but not compared to the O+P+ condition (*z* < 1, *p* = 1.000). In the alpha band, ITPC was higher for the O-P- condition compared to the O-P+ condition (*z* = 6.244, *p* < .001, *d* = 0.716), but not compared to the O+P+ condition (*z* = 1.237, *p* = .433). In the beta band, ITPC was higher for the O-P- condition compared to the O-P+ condition (*z* = 4.837, *p* < .001, *d* = 0.287), but not compared to the O+P+ condition (*z* = -1.815, *p* = .139). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ ($z = 8.552$, $p < .001$, $d = 0.277$) and compared to the O+P+ conditions ($z = 8.567$, $p < .001$, $d = 0.278$). At midline electrode positions, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 2.473$, $p = .027$, $d = 0.401$), but not compared to the O+P+ condition ($z < 1$, $p = .970$) in the delta band. In the theta band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 3.164$, $p = .003$, $d = 0.419$), but not compared to the O+P+ condition ($z = 1.281$, $p = .400$). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 3.465$, $p = .001$, $d = 0.397$), but not compared to the O+P+ condition ($z = 1.463$, $p = .287$). In the beta band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 3.715$, $p < .001$, $d = 0.220$), but reduced compared to the O+P+ condition ($z = -3.625$, $p < .001$, $d = 0.215$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 5.617$, $p < .001$, $d = 0.182$) and compared to the O+P+ condition ($z = 3.286$, $p = .002$, $d = 0.107$). At right electrode positions, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 2.379$, $p = .035$, $d = 0.386$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 2.240$, $p = .050$, $d = 0.297$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 5.176$, $p < .001$, $d = 0.594$), but not compared to the O+P+ condition ($z = 1.900$, $p = .115$). In the beta band, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -3.539$, $p < .001$, $d = 0.210$) and compared to the O+P+ condition ($z = -7.449$, $p < .001$, $d = 0.441$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 4.826$, $p < .001$, $d = 0.157$), but not compared to the O+P+ condition ($z = -1.469$, $p = .284$).

At central electrode sites, main effects of condition ($W(2) = 133.484$, $p < .001$, $R^2 = 5.070 \cdot 10^{-3}$), frequency band ($W(4) = 63.217$, $p < .001$, $R^2 = 2.401 \cdot 10^{-3}$) and lateralization ($W(2) = 16.376$, $p < .001$, $R^2 = 6.220 \cdot 10^{-4}$) were found. The three-way interaction ($W(16) = 53.378$, $p < .001$, $R^2 = 1.576 \cdot 10^{-2}$) was also significant. At left electrode sites, no effect of condition was found in the delta band ($W(2) < 1$, $p = .696$). In the theta band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 5.494$, $p < .001$, $d = 0.728$), but not compared to the O+P+ condition ($z < 1$, $p = .951$). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 4.541$, $p < .001$, $d = 0.521$), but not compared to the O+P+ condition ($z = 1.657$, $p = .195$). In the beta band, ITPC was reduced for the O-P- condition compared to the O+P+ condition ($z = -2.870$, $p = .008$, $d = 0.170$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 8.101$, $p < .001$, $d = 0.263$) and compared to the O+P+ condition ($z = 4.066$, $p < .001$, $d = 0.132$). At midline electrode positions, no effect of condition was found in the delta band (*W*(2) < 1, *p* = .611). In the theta band, ITPC was higher for the O-P- condition compared to the O-P+ condition (*z* = 3.988, *p* < .001, *d* = 0.528), but not compared to the O+P+ condition (*z* < 1, *p* = 1.000). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 2.444, *p* = .029, *d* = 0.280), but not compared to the O+P+ condition (*z* = 1.332, *p* = .366). In the beta band, no effect of condition was found (*W*(2) = 4.267, *p* = .119). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 6.402, *p* < .001, *d* = 0.208) and compared to the O+P+ condition (*z* = 3.725, *p* < .001, *d* = 0.121). At right electrode positions, ITPC was marginally higher for the O-P- compared to the O+P+ condition (*z* = 2.161, *p* = .061, *d* = 0.351), but not compared to the O-P+ condition (*z* < 1, *p* = 1.000) in the delta band. In the theta band, no effect of condition (*W*(2) < 1, *p* = .753) was found. In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 3.530, *p* < .001, *d* = 0.405) and compared to the O+P+ condition (*z* = 2.395, *p* = .033, *d* = 0.275). In the beta band, ITPC was reduced for the O-P- compared to the O+P+ condition (*z* = -2.475, *p* = .027, *d* = 0.147), but not compared to the O-P+ condition (*z* < 1, *p* = 1.000). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 5.469, *p* < .001, *d* = 0.178), but not compared to the O+P+ condition (*z* < 1, *p* = 1.000).

At parietal electrode positions, main effects of condition (*W*(2) = 26.663, *p* < .001, $R^2 = 1.011\cdot10^{-3}$), frequency band (*W*(4) = 57.308, *p* < .001, $R^2 = 2.173\cdot10^{-3}$) and lateralization (*W*(2) = 12.437, *p* = .002, $R^2 = 4.716\cdot10^{-4}$) were found. The three-way interaction (*W*(16) = 55.045, *p* < .001, $R^2 = 1.679\cdot10^{-2}$) was also significant. At left electrode sites, no effect of condition was found in the delta band (*W*(2) = 4.603, *p* = .100). In the theta band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 3.680, *p* < .001, *d* = 0.488), but not compared to the O+P+ condition (*z* < 1, *p* = 1.000). In the alpha band, ITPC was marginally higher for the O-P- compared to the O-P+ condition (*z* = 2.155, *p* = .062, *d* = 0.247), but not compared to the O+P+ condition (*z* < 1, *p* = 1.000). In the beta band, ITPC was reduced for the O-P- compared to the O-P+ condition (*z* = -7.533, *p* < .001, *d* = 0.446), but not compared to the O+P+ condition (*z* < 1, *p* = .942). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 9.074, *p* < .001, *d* = 0.294) and compared to the O+P+ condition (*z* = 3.026, *p* = .005, *d* = 0.098). At midline electrode sites, no difference in ITPC was found between the O-P- and the O-P+ condition (*z* = -1.878, *p* = .121) nor between the O-P- and the O+P+ condition (*z* = 1.109, *p* = .535) in the delta band. In the theta band, ITPC was reduced for the O-P- compared to the O+P+ condition (*z* = -2.264, *p* = .047, *d* = 0.300), but not compared to the O-P+ condition (*z* < 1, *p* = 1.000). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition (*z* = 4.066, *p* < .001, *d* = 0.466) and compared to the O+P+ condition (*z* =

2.711, $p = .013$, $d = 0.311$). In the beta band, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -3.959$, $p < .001$, $d = 0.235$) and compared to the O+P+ condition ($z = -2.556$, $p = .021$, $d = 0.151$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 6.231$, $p < .001$, $d = 0.202$), but not compared to the O+P+ condition ($z = 1.317$, $p = .376$). At right electrode sites, no difference was found between the O-P- and the O-P+ condition ($z < 1$, $p = 1.000$) nor between the O-P- compared to the O+P+ condition ($z = 1.683$, $p = .185$) in the delta band. In the theta band, ITPC was reduced for the O-P- condition compared to the O+P+ condition ($z = -2.532$, $p = .023$, $d = 0.335$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the alpha band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 2.442$, $p = .029$, $d = 0.280$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -3.949$, $p < .001$, $d = 0.234$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 4.035$, $p < .001$, $d = 0.131$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$).

2.2 TF results of Experiment 2 on the role of orthography on auditory priming

TF power. For the orthographic time window, main effects of condition ($W(2) = 224.027$, $p < .001$, $R^2 = 3.001 \cdot 10^{-3}$), frequency band ($W(4) = 2{,}679.815$, $p < .001$, $R^2 = 3.590 \cdot 10^{-2}$), anterior-posterior distribution ($W(2) = 232.526$, $p < .001$, $R^2 = 3.115 \cdot 10^{-3}$) and lateralization ($W(2) = 137.757$, $p < .001$, $R^2 = 1.846 \cdot 10^{-3}$) were found. The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization ($W(32) = 54.757$, $p = .007$, $R^2 = 6.417 \cdot 10^{-2}$) also reached significance.

Subsequent analyses per anterior-posterior distribution showed main effects of condition ($W(2) = 86.436$, $p < .001$, $R^2 = 3.439 \cdot 10^{-3}$), frequency band ($W(4) = 1{,}073.703$, $p < .001$, $R^2 = 4.271 \cdot 10^{-2}$) and lateralization ($W(2) = 55.096$, $p < .001$, $R^2 = 2.192 \cdot 10^{-3}$) for the frontal ROI. The interaction between condition, frequency band and lateralization ($W(16) = 30.365$, $p = .016$, $R^2 = 5.879 \cdot 10^{-2}$) was also significant. For left-lateralized electrode sites, no effect of condition ($W(2) = 1.655$, $p = .437$) was found in the delta band. In the theta band, power was slightly reduced for the O+P+ compared to the O-P+ ($z = -2.176$, $p = .059$, $d = 0.314$) and reduced compared to the O-P- condition ($z = -2.655$, $p = .016$, $d = 0.383$). In the alpha band, power was reduced for the O+P+ condition compared to the O-P- condition ($z = -3.426$, $p = .001$, $d = 0.428$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, no effect of condition ($W(2) = 3.034$, $p = .219$) was found. In the gamma band, power was higher for the O+P+ condition compared to the O-P+ condition ($z = 7.602$, $p < .001$, $d = 0.269$) and compared to the O-P- condition ($z = 4.822$, $p < .001$, $d = 0.171$). At midline electrode sites, no effect of condition was found in the delta band ($W(2) = 2.830$, $p = .243$). In the theta band, power was reduced for the O+P+ compared to the O-P+ ($z = -3.457$, $p = .001$, $d = 0.499$) and compared to the O-P- condition ($z = -3.511$, $p < .001$, $d = 0.507$). In the alpha band, power was lower for the O+P+ compared to the O-P- condition ($z = -3.425$, $p = .001$, $d = 0.428$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -2.747$, $p = .012$, $d = 0.177$), but not compared to the O-P- condition ($z = -1.947$, $p = .103$). In the gamma band, power was higher for the O+P+ compared to the O-P+ ($z = 9.511$, $p < .001$, $d = 0.336$) and compared to the O-P- condition ($z = 4.132$, $p < .001$, $d = 0.146$). At right electrode positions, no effect of condition was found in the delta band ($W(2) = 1.888$, $p = .389$) nor in the theta band ($W(2) = 1.193$, $p = .551$). In the alpha band, no difference in power was found for the O+P+ compared to the O-P+ condition ($z < 1$, $p = .693$) nor compared to the O-P- condition ($z = -1.796$, $p = .145$). In the beta band, power was reduced for the O+P+ compared to the O-P- condition ($z = -3.372$, $p = .002$, $d = 0.218$), but not compared to the O-P+ condition ($z < 1$, $p = .990$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 6.153$, $p < .001$, $d = 0.218$), but not compared to the O-P- condition ($z = -1.217$, $p = .447$).

In the central ROI, main effects of condition ($W(2) = 92.540$, $p < .001$, $R^2 = 3.622\cdot10^{-3}$), frequency band ($W(4) = 1{,}146.858$, $p < .001$, $R^2 = 4.489\cdot10^{-2}$) and lateralization ($W(2) = 74.115$, $p < .001$, $R^2 = 2.901\cdot10^{-3}$) were found. The interaction between condition, frequency band and lateralization ($W(16) = 90.797$, $p < .001$, $R^2 = 7.088\cdot10^{-2}$) was also significant. At left electrode sites, no effect of condition was found in the delta band ($W(2) = 2.919$, $p = .232$). In the theta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -2.838$, $p = .009$, $d = 0.410$) and compared to the O-P- condition ($z = -2.785$, $p = .011$, $d = 0.402$). In the alpha band, power was lower for the O+P+ compared to the O-P- condition ($z = -3.458$, $p = .001$, $d = 0.432$), but not compared to the O-P+ condition ($z = 1.088$, $p = .554$). In the beta band, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.358$, $p = .037$, $d = 0.152$), but reduced compared to the O-P- condition ($z = -3.986$, $p < .001$, $d = 0.257$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 7.359$, $p < .001$, $d = 0.260$) and compared to the O-P- condition ($z = 10.095$, $p < .001$, $d = 0.357$). At midline electrode positions, no effect of condition was found in the delta band ($W(2) = 4.528$, $p = .104$). In the theta band, power was reduced for the O+P+ condition compared to the O-P+ condition ($z = -3.424$, $p = .001$, $d = 0.494$), but not compared to the O-P- condition ($z = -1.569$, $p = .233$). In the alpha band, no effect of condition was found ($W(2) = 3.403$, $p = .182$). In the beta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -2.734$, $p = .013$, $d = 0.176$) and compared to the O-P- condition ($z = -5.115$, $p < .001$, $d = 0.330$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 13.516$, $p < .001$, $d = 0.478$) and compared to the O-P- condition ($z = 7.120$, $p < .001$, $d = 0.252$). At right electrode positions, no effect of condition was found in the delta band ($W(2) = 3.878$, $p = .144$) nor in the theta band ($W(2) = 2.460$, $p = .292$). In the alpha band, power was higher for the O+P+ compared to the O-P+ condition ($z = 2.632$, $p = .017$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the beta band, power was reduced for the O+P+ compared to the O-P+ ($z = -4.798$, $p < .001$, $d = 0.310$) and compared to the O-P- condition ($z = -8.155$, $p < .001$, $d = 0.526$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 5.107$, $p < .001$, $d = 0.181$), but not compared to the O-P- condition ($z = -1.145$, $p = .504$).

At parietal electrode sites, main effects of condition ($W(2) = 56.609$, $p < .001$, $R^2 = 2.237 \cdot 10^{-3}$), frequency band ($W(4) = 712.918$, $p < .001$, $R^2 = 2.816 \cdot 10^{-2}$) and lateralization ($W(2) = 22.476$, $p < .001$, $R^2 = 8.880 \cdot 10^{-4}$) were found. The interaction between condition, frequency band and lateralization ($W(16) = 43.653$, $p < .001$, $R^2 = 5.405 \cdot 10^{-2}$) was also significant. At left electrode positions, no effect of condition was found in the delta band ($W(2) = 3.306$, $p = .192$). In the theta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -2.879$, $p = .008$, $d = 0.416$), but not compared to the O-P- condition ($z < 1$, $p = .677$). In the alpha band, no differences in power were found between the O+P+ and the O-P+ condition ($z = 1.688$, $p = 0.183$) nor compared to the O-P- condition ($z = -1.076$, $p = .564$). In the beta band, power was reduced for the O+P+ compared to the O-P- condition ($z = -9.434$, $p < .001$, $d = 0.609$), but not compared to the O-P+ condition ($z < 1$, $p = 0.654$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 6.565$, $p < .001$, $d = 0.232$) and compared to the O-P- condition ($z = 8.471$, $p < .001$, $d = 0.300$). At midline electrode sites, power was marginally higher for the O+P+ condition compared to the O-P- condition ($z = 2.141$, $p = .065$, $d = 0.378$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, power was reduced for the O+P+ condition compared to the O-P+ condition ($z = -4.117$, $p < .001$, $d = 0.594$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the alpha band, power was marginally reduced for the O+P+ compared to the O-P- condition ($z = -2.016$, $p = .088$, $d = 0.252$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -5.752$, $p < .001$, $d = 0.371$) and compared to the O-P- condition ($z = -12.465$, $p < .001$, $d = 0.805$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition

($z = 10.586$, $p < .001$, $d = 0.374$) and compared to the O-P- condition ($z = 7.192$, $p < .001$, $d = 0.254$). At right electrode sites, power was higher for the O+P+ compared to the O-P- condition ($z = 4.047$, $p < .001$, $d = 0.715$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, power was lower for the O+P+ compared to the O-P+ condition ($z = -2.339$, $p = .039$, $d = 0.338$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the alpha band, no effect of condition was found ($W(2) = 2.143$, $p = .342$). In the beta band, power was reduced for the O+P+ compared to the O-P+ condition ($z = -6.929$, $p < .001$, $d = 0.447$) and compared to the O-P- condition ($z = -10.501$, $p < .001$, $d = 0.678$). In the gamma band, power was higher for the O+P+ compared to the O-P+ condition ($z = 11.353$, $p < .001$, $d = 0.401$) and compared to the O-P- condition ($z = 6.992$, $p < .001$, $d = 0.247$).

For the phonological time window, main effects of condition ($W(2) = 258.652$, $p < .001$, $R^2 = 3.273 \cdot 10^{-3}$), frequency band ($W(4) = 5{,}566.392$, $p < .001$, $R^2 = 7.044 \cdot 10^{-2}$), anterior-posterior distribution ($W(2) = 602.073$, $p < .001$, $R^2 = 7.619 \cdot 10^{-3}$) and lateralization ($W(2) = 219.369$, $p < .001$, $R^2 = 2.776 \cdot 10^{-3}$) were found. The three-way interactions between condition, frequency, band and anterior-posterior distribution ($W(16) = 93.979$, $p < .001$, $R^2 = 9.889 \cdot 10^{-2}$), condition, frequency band and lateralization ($W(16) = 49.431$, $p < .001$, $R^2 = 9.676 \cdot 10^{-2}$) and between condition, anterior-posterior distribution and lateralization ($W(8) = 20.588$, $p = .008$, $R^2 = 1.444 \cdot 10^{-2}$) were significant. The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization ($W(32) = 31.659$, $p = .484$) was not significant. The interaction with the highest significance was analyzed further, which was the interaction between condition, frequency band and anterior-posterior distribution.

At frontal electrode sites, main effects of condition ($W(2) = 112.864$, $p < .001$, $R^2 = 4.220 \cdot 10^{-3}$), frequency band ($W(4) = 1{,}990.762$, $p < .001$, $R^2 = 7.442 \cdot 10^{-2}$) and lateralization ($W(2) = 137.816$, $p < .001$, $R^2 = 5.153 \cdot 10^{-3}$) were found. The interactions between condition and frequency band ($W(8) = 262.101$, $p < .001$, $R^2 = 8.841 \cdot 10^{-2}$) and between condition and lateralization ($W(4) = 25.096$, $p < .001$, $R^2 = 1.031 \cdot 10^{-2}$) were significant. The three-way interaction between condition, frequency band and lateralization ($W(16) = 20.644$, $p = .193$) was not significant. In the delta band, power was reduced for the O-P- compared to the O-P+ condition ($z = -2.486$, $p = .026$, $d = 0.254$), but not compared to the O+P+ condition ($z = -1.840$, $p = .131$). In the theta band, power was higher for the O-P- compared to the O+P+ condition ($z = 2.461$, $p = .028$, $d = 0.205$), but not compared to the O-P+ condition ($z = -1.575$, $p = .231$). In the alpha band, power was higher for the O-P- compared to the O-P+ ($z = 3.651$, $p < .001$, $d = 0.264$) and compared to the O+P+ condition ($z = 2.347$, $p = .038$, $d = 0.169$). In the beta band, power was higher for the O-P- compared to the O-P+ condition (left: $z = 6.752$, $p < .001$,

$d = 0.436$; midline: $z = 8.200$, $p < .001$, $d = 0.529$; right: $z = 10.685$, $p < .001$, $d = 0.690$) and compared to the O+P+ condition (left: $z = 3.383$, $p = .001$, $d = 0.218$; midline: $z = 7.241$, $p < .001$, $d = 0.467$; right: $z = 9.611$, $p < .001$, $d = 0.620$). Both effects were more right-lateralized. In the gamma band, power was higher for the O-P- compared to the O-P+ condition (left: $z = 2.033$, $p = .084$, $d = 0.072$; midline: $z = 3.351$, $p = .002$, $d = 0.118$; right: $z = 3.896$, $p < .001$, $d = 0.138$), but reduced compared to the O+P+ condition (left: $z = -8.388$, $p < .001$, $d = 0.297$; midline: $z = -6.028$, $p < .001$, $d = 0.213$; right: $z < 1$, $p = 1.000$). The first effect was more right-lateralized, while the latter effect was stronger at left electrode positions.

At the central ROI, main effects of condition ($W(2) = 125.046$, $p < .001$, $R^2 = 4.548 \cdot 10^{-3}$), frequency band ($W(4) = 2{,}445.993$, $p < .001$, $R^2 = 8.895 \cdot 10^{-2}$) and lateralization ($W(2) = 62.602$, $p < .001$, $R^2 = 2.277 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 39.904$, $p < .001$, $R^2 = 0.123$) was also significant. At left electrode sites, power was higher for the O-P- compared to the O-P+ condition ($z = 2.795$, $p = .010$, $d = 0.494$), but not compared to the O+P+ condition ($z = 1.157$, $p = 0.494$) in the delta band. In the theta band, no effect of condition ($W(2) = 2.302$, $p = .316$) was found. In the alpha band, power was higher for the O-P- condition compared to the O-P+ condition ($z = 3.186$, $p = .003$, $d = 0.398$), but not compared to the O+P+ condition ($z = 1.872$, $p = .123$). In the beta band, power was higher for the O-P- compared to the O-P+ ($z = 10.571$, $p < .001$, $d = 0.682$) and compared to the O+P+ condition ($z = 7.445$, $p < .001$, $d = 0.481$). In the gamma band, power was reduced for the O-P- condition compared to the O-P+ condition ($z = -2.724$, $p = .013$, $d = 0.096$) and compared to the O+P+ condition ($z = -8.680$, $p < .001$, $d = 0.307$). At midline electrode positions no effect of condition was found in the delta band ($W(2) = 1.936$, $p = .380$), in the theta band ($W(2) = 2.755$, $p = .252$) nor in the alpha band ($W(2) = 3.088$, $p = .214$). In the beta band, power was higher for the O-P- condition compared to the O-P+ condition ($z = 10.365$, $p < .001$, $d = 0.669$) and compared to the O+P+ condition ($z = 10.121$, $p < .001$, $d = 0.653$). In the gamma band, power was higher for the O-P- compared to the O-P+ condition ($z = 4.111$, $p < .001$, $d = 0.145$), but reduced compared to the O+P+ condition ($z = -6.752$, $p < .001$, $d = 0.239$). At right electrode sites, no effect of condition was found in the delta band ($W(2) = 2.091$, $p = .352$) nor in the theta band ($W(2) = 1.131$, $p = .568$). In the alpha band, power was higher for the O-P- compared to the O-P+ condition ($z = 3.807$, $p < .001$, $d = 0.476$) and compared to the O+P+ condition ($z = 2.107$, $p = .070$, $d = 0.263$). In the beta band, power was higher for the O-P- compared to the O-P+ condition ($z = 11.231$, $p < .001$, $d = 0.725$) and compared to the O+P+ condition ($z = 12.360$, $p < .001$, $d = 0.798$). In the gamma band, power was reduced for the O-P- compared to the O+P+ condition (z = -5.029, p < .001, d = 0.178), but not compared to the O-P+ condition (z < 1, p = .837).

At parietal electrode sites, main effects of condition (W(2) = 42.642, p < .001, R^2 = 1.616·10^{-3}), frequency band (W(4) = 1,514.934, p < .001, R^2 = 5.741·10^{-2}) and lateralization (W(2) = 44.508, p < .001, R^2 = 1.687·10^{-3}) were found. The interaction between condition and frequency band (W(8) = 531.476, p < .001, R^2 = 7.913·10^{-2}) also reached significance. Neither the interaction between condition and lateralization (W(4) = 2.160, p = .706) nor the three-way interaction (W(16) = 22.564, p = .126) were significant. In the delta band, power was reduced for the O-P- compared to the O+P+ condition (z = -2.630, p = .017, d = 0.268), but not compared to the O-P+ condition (z < 1, p = .984). In the theta band, no effect of condition was found (W(2) = 1.278, p = .528). In the alpha band, power was higher for the O-P- compared to the O-P+ condition (z = 4.990, p < .001, d = 0.360) and compared to the O+P+ condition (z = 5.884, p < .001, d = 0.425). In the beta band, power was higher for the O-P- compared to the O-P+ condition (left: z = 10.920, p < .001, d = 0.705; midline: z = 8.858, p < .001, d = 0.572; right: z = 6.862, p < .001, d = 0.738) and compared to the O+P+ condition (left: z = 13.316, p < .001, d = 0.860; midline: z = 12.877, p < .001, d = 0.831; right: z = 11.437, p < .001, d = 0.738). Both effects showed a tendency towards a left-lateralization. In the gamma band, power was reduced for the O-P- compared to the O-P+ condition (left: z = -3.315, p = .002, d = 0.117; midline: z < 1, p = 1.000; right: z < 1, p = 1.000) and compared to the O+P+ condition (left: z = -8.434, p < .001, d = 0.298; midline: z = -7.744, p < .001, d = 0.274; right: z = -9.186, p < .001, d = 0.325). The first effect was strongly left-lateralized, while the latter effect was broadly distributed.

ITPC. For the orthographic time window, main effects of condition (W(2) = 231.226, p < .001, R^2 = 3.428·10^{-3}), frequency band (W(4) = 832.450, p < .001, R^2 = 1.234·10^{-2}) and anterior-posterior distribution (W(2) = 6.581, p = .037, R^2 = 9.756·10^{-5}) were found. The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization (W(32) = 66.121, p < .001, R^2 = 2.939·10^{-2}) also reached significance.

In the frontal ROI, main effects of condition (W(2) = 94.602, p < .001, R^2 = 4.178·10^{-3}), frequency band (W(4) = 376.582, p < .001, R^2 = 1.663·10^{-2}) and lateralization (W(2) = 12.792, p = .002, R^2 = 5.649·10^{-4}) were found. The three-way interaction between condition, frequency band and lateralization (W(16) = 37.852, p = .002, R^2 = 3.685·10^{-2}) also reached significance. At left electrode positions, ITPC was higher for the O+P+ compared to the O-P- condition (z = 3.210, p = .003, d = 0.567), but not compared to the O-P+ condition (z < 1, p = 1.000) in the delta band. In the theta band, ITPC was higher for the O+P+ compared to the O-P- condition

($z = 2.789$, $p = .011$, $d = 0.403$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the alpha band, no effect of condition was found ($W(2) < 1$, $p = .618$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -2.727$, $p = .013$, $d = 0.176$) and compared to the O-P- condition ($z = -3.331$, $p = .002$, $d = 0.215$). In the gamma band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -2.518$, $p = .024$, $d = 0.089$) and compared to the O-P- condition ($z = -3.763$, $p < .001$, $d = 0.133$). At midline electrode sites, ITPC was higher for the O+P+ compared to the O-P- condition ($z = 2.368$, $p = .036$, $d = 0.419$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, ITPC was higher for the O+P+ compared to the O-P- condition ($z = 5.340$, $p < .001$, $d = 0.771$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the alpha band, ITPC was marginally higher for the O+P+ compared to the O-P- condition ($z = 2.080$, $p = .075$, $d = 0.260$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -3.340$, $p = .002$, $d = 0.216$) and compared to the O-P- condition ($z = -2.333$, $p = .039$, $d = 0.151$). In the gamma band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -8.966$, $p < .001$, $d = 0.317$) and compared to the O-P- condition ($z = -4.471$, $p < .001$, $d = 0.158$). At right electrode sites, no effect of condition was found in the delta band ($W(2) = 4.060$, $p = .131$). In the theta band, ITPC was higher for the O+P+ compared to the O-P- condition ($z = 5.526$, $p < .001$, $d = 0.798$), but not compared to the O-P+ condition ($z = 1.509$, $p = .263$). In the alpha band, ITPC was marginally higher for the O+P+ compared to the O-P- condition ($z = 2.158$, $p = .062$, $d = 0.270$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -7.277$, $p < .001$, $d = 0.470$) and compared to the O-P- condition ($z = -7.302$, $p < .001$, $d = 0.471$). In the gamma band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -4.776$, $p < .001$, $d = 0.169$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$).

At central electrode sites, main effects of condition ($W(2) = 66.286$, $p < .001$, $R^2 = 2.925 \cdot 10^{-3}$), frequency band ($W(4) = 347.293$, $p < .001$, $R^2 = 1.532 \cdot 10^{-2}$) and lateralization ($W(2) = 11.713$, $p = .003$, $R^2 = 5.169 \cdot 10^{-4}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 78.978$, $p < .001$, $R^2 = 3.096 \cdot 10^{-2}$) also reached significance. At left electrode positions, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z = -1.561$, $p = .237$) nor compared to the O-P- condition ($z = 1.640$, $p = .202$) in the delta band. In the theta band, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z = -1.395$, $p = .326$) nor compared to the O-P- condition ($z = 1.916$, $p = .111$). In the alpha band, ITPC was reduced for the O+P+ compared to the O-P+

condition ($z = -3.229$, $p = .003$, $d = 0.404$), but not compared to the O-P- condition ($z < 1$, $p = 1.000$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -3.751$, $p < .001$, $d = 0.242$) and marginally reduced compared to the O-P- condition ($z = -2.062$, $p = .079$, $d = 0.133$). In the gamma band, no effect of condition was found ($W(2) = 2.737$, $p = .255$). At midline electrode sites, ITPC was higher for the O+P+ condition compared to the O-P- condition ($z = 2.869$, $p = .008$, $d = 0.507$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, ITPC was higher for the O+P+ condition compared to the O-P- condition ($z = 3.496$, $p < .001$, $d = 0.505$), but not compared to the O-P+ condition ($z = 1.363$, $p = .346$). In the alpha band, no effect of condition was found ($W(2) = 3.886$, $p = .143$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -2.658$, $p = .016$, $d = 0.172$) and marginally reduced compared to the O-P- condition ($z = -1.969$, $p = .098$, $d = 0.127$). In the gamma band, ITPC was reduced for the O+P+ condition compared to the O-P+ condition ($z = -3.709$, $p < .001$, $d = 0.131$), but not compared to the O-P- condition ($z = -1.728$, $p = .168$). At right electrode sites, no effect of condition was found in the delta band ($W(2) = 2.586$, $p = .275$). In the theta band, ITPC was higher for the O+P+ compared to the O-P- condition ($z = 2.907$, $p = .007$, $d = 0.420$), but not compared to the O-P+ condition ($z = 1.735$, $p = .166$). In the alpha band, no effect of condition ($W(2) < 1$, $p = .959$) was found. In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -5.005$, $p < .001$, $d = 0.323$) and compared to the O-P- condition ($z = -8.029$, $p < .001$, $d = 0.518$). In the gamma band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -6.377$, $p < .001$, $d = 0.226$) and compared to the O-P- condition ($z = -2.250$, $p = .049$, $d = 0.080$).

At parietal electrode sites, main effects of condition ($W(2) = 77.801$, $p < .001$, $R^2 = 3.483 \cdot 10^{-3}$) and frequency band ($W(4) = 214.096$, $p < .001$, $R^2 = 9.585 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 36.283$, $p = .003$, $R^2 = 2.057 \cdot 10^{-2}$) was significant. At left electrode positions, no effect of condition was found in the delta band ($W(2) = 1.686$, $p = .430$). In the theta band, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z = -1.368$, $p = .342$) nor compared to the O-P- condition ($z < 1$, $p = .872$). In the alpha band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -2.281$, $p = .045$, $d = 0.285$) and compared to the O-P- condition ($z = -4.907$, $p < .001$, $d = 0.613$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -2.412$, $p = .032$, $d = 0.156$) and marginally reduced compared to the O-P- condition ($z = -1.960$, $p = .100$, $d = 0.127$). In the gamma band, no effect of condition ($W(2) = 2.131$, $p = .345$) was found. At midline electrode positions, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z = -1.382$, $p = .334$) nor compared to the O-P-condition ($z < 1$, $p = .761$) in the delta band. In the theta band, no effect of condition ($W(2) = 2.171$, $p = .338$) was found. In the alpha band, ITPC was reduced for the O+P+ condition compared to the O-P- condition ($z = -4.244$, $p < .001$, $d = 0.530$), but not compared to the O-P+ condition ($z = -1.479$, $p = .278$). In the beta band, no effect of condition ($W(2) = 3.082$, $p = .214$) was found. In the gamma band, ITPC was reduced for the O+P+ condition compared to the O-P+ condition ($z = -5.753$, $p < .001$, $d = 0.203$), but not compared to the O-P- condition ($z = -1.498$, $p = .269$). At right electrode sites, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z < 1$, $p = .951$) nor compared to the O-P- condition ($z = 1.445$, $p = .297$) in the delta band. In the theta band, no effect of condition ($W(2) = 3.044$, $p = .218$) was found. In the alpha band, no difference in ITPC was found for the O+P+ compared to the O-P+ condition ($z = 1.330$, $p = .367$) nor compared to the O-P- condition ($z = -1.948$, $p = .103$). In the beta band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -3.109$, $p = .004$, $d = 0.201$) and compared to the O-P- condition ($z = -2.689$, $p = .014$, $d = 0.174$). In the gamma band, ITPC was reduced for the O+P+ compared to the O-P+ condition ($z = -7.426$, $p < .001$, $d = 0.263$) and compared to the O-P- condition ($z = -2.257$, $p = .048$, $d = 0.080$).

For the phonological time window, main effects of condition ($W(2) = 193.865$, $p < .001$, $R^2 = 2.875 \cdot 10^{-3}$), frequency band ($W(4) = 412.745$, $p < .001$, $R^2 = 6.120 \cdot 10^{-3}$), anterior-posterior distribution ($W(2) = 21.557$, $p < .001$, $R^2 = 3.197 \cdot 10^{-4}$) and lateralization ($W(2) = 4.959$, $p = .084$, $R^2 = 7.354 \cdot 10^{-5}$) were found. The four-way interaction between condition, frequency band, anterior-posterior distribution and lateralization ($W(32) = 64.348$, $p < .001$, $R^2 = 2.428 \cdot 10^{-2}$) also reached significance.

At the frontal ROI, main effects of condition ($W(2) = 51.056$, $p < .001$, $R^2 = 2.253 \cdot 10^{-3}$), frequency band ($W(4) = 182.673$, $p < .001$, $R^2 = 8.059 \cdot 10^{-3}$) and lateralization ($W(2) = 38.202$, $p < .001$, $R^2 = 1.686 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 31.122$, $p = .013$, $R^2 = 3.159 \cdot 10^{-2}$) also reached significance. At left electrode positions, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -2.709$, $p = .014$, $d = 0.479$) and compared to the O+P+ condition ($z = -3.043$, $p = .005$, $d = 0.538$) in the delta band. In the theta band, ITPC was lower for the O-P- compared to the O-P+ condition ($z = -3.002$, $p = .005$, $d = 0.433$) and compared to the O+P+ condition ($z = -3.884$, $p < .001$, $d = 0.561$). In the alpha band, no effect of condition ($W(2) = 4.253$, $p = .119$) was found. In the beta band, ITPC was marginally higher for the O-P- condition compared to the O-P+ condition ($z = 2.012$, $p = .089$, $d = 0.130$) and higher compared to the O+P+ condition ($z = 4.839$, $p < .001$, $d = 0.312$). In the gamma band, no effect of condition ($W(2) < 1$, $p = .967$) was found. At midline sites, ITPC was reduced for the O-P- condition compared to the O-P+

condition ($z = -2.334$, $p = .039$, $d = 0.413$) and marginally reduced compared to the O+P+ condition ($z = -2.190$, $p = .057$, $d = 0.387$) in the delta band. In the theta band, ITPC was lower for the O-P- compared to the O-P+ condition ($z = -4.513$, $p < .001$, $d = 0.651$) and compared to the O+P+ condition ($z = -5.426$, $p < .001$, $d = 0.783$). In the alpha band, ITPC was lower for the O-P- compared to the O+P+ condition ($z = -3.462$, $p = .001$, $d = 0.433$), but not compared to the O-P+ condition ($z = -1.874$, $p = .122$). In the beta band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 4.252$, $p < .001$, $d = 0.275$), but not compared to the O-P+ condition ($z < 1$, $p = .890$). In the gamma band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 6.885$, $p < .001$, $d = 0.243$), but not compared to the O-P+ condition ($z = 1.271$, $p = .408$). At right electrode positions, no effect of condition was found in the delta band ($W(2) = 2.835$, $p = .242$). In the theta band, ITPC was reduced for the O-P- condition compared to the O-P+ condition ($z = -4.346$, $p < .001$, $d = 0.627$) and compared to the O+P+ condition ($z = -5.421$, $p < .001$, $d = 0.783$). In the alpha band, ITPC was lower for the O-P- compared to the O+P+ condition ($z = -4.458$, $p < .001$, $d = 0.557$), but not compared to the O-P+ condition ($z = -1.115$, $p = .530$). In the beta band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 7.659$, $p < .001$, $d = 0.494$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 7.044$, $p < .001$, $d = 0.249$), but not compared to the O-P+ condition ($z < 1$, $p = .931$).

At central electrode positions, main effects of condition ($W(2) = 71.815$, $p < .001$, $R^2 = 3.191 \cdot 10^{-3}$), frequency band ($W(4) = 192.629$, $p < .001$, $R^2 = 8.560 \cdot 10^{-3}$) and lateralization ($W(2) = 7.083$, $p = .029$, $R^2 = 3.148 \cdot 10^{-4}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 54.131$, $p < .001$, $R^2 = 2.228 \cdot 10^{-2}$) was also significant. At left electrode positions, ITPC was reduced for the O-P- condition compared to the O-P+ condition ($z = -2.347$, $p = .038$, $d = 0.415$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$) in the delta band. In the theta band, ITPC was reduced for the O-P- condition compared to the O-P+ condition ($z = -3.774$, $p < .001$, $d = 0.545$) and compared to the O+P+ condition ($z = -3.536$, $p < .001$, $d = 0.510$). In the alpha band, ITPC was lower for the O-P- compared to the O-P+ condition ($z = -2.584$, $p = .020$, $d = 0.323$), but not compared to the O+P+ condition ($z = -1.394$, $p = .327$). In the beta band, ITPC was lower for the O-P- compared to the O-P+ condition ($z = -4.277$, $p < .001$, $d = 0.276$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$). In the gamma band, ITPC was lower for the O-P- condition compared to the O-P+ condition ($z = -3.176$, $p = .003$, $d = 0.112$), but not compared to the O+P+ condition ($z < 1$, $p = .949$). At midline sites, no effect of condition was found in the delta band ($W(2) = 3.451$, $p = .178$). In the theta band, ITPC was reduced for the O-P- compared to the O-P+ condition

($z = -2.843$, $p = .009$, $d = 0.410$) and compared to the O+P+ condition ($z = -4.193$, $p < .001$, $d = 0.605$). In the alpha band, ITPC was marginally lower for the O-P- compared to the O+P+ condition ($z = -1.999$, $p = .091$, $d = 0.250$), but not compared to the O-P+ condition ($z = -1.730$, $p = .167$). In the beta band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 3.060$, $p = .004$, $d = 0.198$), but not compared to the O-P+ condition ($z = 1.155$, $p = .496$). In the gamma band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 3.644$, $p < .001$, $d = 0.129$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). At right electrode positions, no effect of condition was found in the delta band ($W(2) < 1$, $p = .818$), in the theta band ($W(2) = 1.912$, $p = .384$) nor in the alpha band ($W(2) = 3.024$, $p = .221$). In the beta band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 4.895$, $p < .001$, $d = 0.316$), but not compared to the O-P+ condition ($z = 1.150$, $p = .500$). In the gamma band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 4.615$, $p < .001$, $d = 0.163$), but not compared to the O-P+ condition ($z = -1.939$, $p = .105$).

At the parietal ROI, main effects of condition ($W(2) = 92.156$, $p < .001$, $R^2 = 4.093 \cdot 10^{-3}$) and frequency band ($W(4) = 162.907$, $p < .001$, $R^2 = 7.235 \cdot 10^{-3}$) were found. The three-way interaction between condition, frequency band and lateralization ($W(16) = 54.264$, $p < .001$, $R^2 = 1.796 \cdot 10^{-2}$) was also significant. At left electrode sites, no effect of condition was found in the delta band ($W(2) = 3.405$, $p = .182$) nor in the theta band ($W(2) = 3.997$, $p = .136$). In the alpha band, ITPC was higher for the O-P- condition compared to the O-P+ condition ($z = 2.598$, $p = .019$, $d = 0.325$) and compared to the O+P+ condition ($z = 3.501$, $p < .001$, $d = 0.438$). In the beta band, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -3.110$, $p = .004$, $d = 0.201$), but not compared to the O+P+ condition ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 2.223$, $p = .053$, $d = 0.079$) and compared to the O+P+ condition ($z = 4.136$, $p < .001$, $d = 0.146$). At midline sites, no effect of condition was found in the delta band ($W(2) = 3.190$, $p = .203$) nor in the theta band ($W(2) = 1.980$, $p = .372$). In the alpha band, ITPC was higher for the O-P- compared to the O-P+ condition ($z = 2.942$, $p = .007$, $d = 0.368$) and compared to the O+P+ condition ($z = 4.010$, $p < .001$, $d = 0.501$). In the beta band, no effect of condition ($W(2) = 3.497$, $p = .174$) was found. In the gamma band, ITPC was higher for the O-P- compared to the O+P+ condition ($z = 5.619$, $p < .001$, $d = 0.199$), but not compared to the O-P+ condition ($z < 1$, $p = 1.000$). At right electrode positions, no effect of condition was found in the delta band ($W(2) < 1$, $p = .939$). In the theta band, ITPC was marginally higher for the O-P- compared to the O+P+ condition ($z = 2.161$, $p = .061$), but not compared to the O-P+ condition ($z = 1.534$, $p = .250$). Neither the alpha band ($W(2) = 4.525$, $p = .104$) nor the beta band ($W(2) < 1$, $p = .916$) showed an effect of condition. In the gamma band, ITPC was reduced for the O-P- compared to the O-P+ condition ($z = -3.083$, $p = .004$, $d = 0.109$), but enhanced compared to the O+P+ condition ($z = 5.448$, $p < .001$, $d = 0.193$).

2.3 TF results of Experiment 2 on cross-modal transposed letter priming

TF power. Only results of interest are reported. The overall model showed main effects of condition ($W(2) = 100.720$, $p < .001$, $R^2 = 7.640 \cdot 10^{-5}$), time window ($W(1) = 4{,}535.400$, $p < .001$, $R^2 = 3.440 \cdot 10^{-3}$), frequency band ($W(4) = 163{,}220.000$, $p < .001$, $R^2 = 1.238 \cdot 10^{-1}$) and ROI ($W(3) = 7{,}011.800$, $p < .001$, $R^2 = 5.319 \cdot 10^{-3}$). The six-way interaction between condition, language, frequency band, time window, prime duration and ROI ($W(24) = 150.100$, $p < .001$, $R^2 = 1.845 \cdot 10^{-1}$) also reached significance. Subsequent analysis by prime duration showed for a duration of 66.67 ms a main effect of condition ($W(2) = 122.493$, $p < .001$, $R^2 = 1.816 \cdot 10^{-4}$), time window ($W(1) = 2{,}342.100$, $p < .001$, $R^2 = 3.472 \cdot 10^{-3}$), frequency band ($W(4) = 71{,}272.415$, $p < .001$, $R^2 = 1.057 \cdot 10^{-1}$) and ROI ($W(3) = 6{,}869.132$, $R^2 = 1.018 \cdot 10^{-2}$). The five-way interaction between condition, language, time window, frequency band and ROI ($W(24) = 144.510$, $p < .001$, $R^2 = 1.669 \cdot 10^{-1}$) was also significant. Subsequent analyses for the N250 time window showed a main effect of condition ($W(2) = 33.569$, $p < .001$, $R^2 = 1.029 \cdot 10^{-4}$), frequency band ($W(4) = 38{,}025.153$, $p < .001$, $R^2 = 1.166 \cdot 10^{-1}$) and ROI ($W(3) = 3{,}504.409$, $p < .001$, $R^2 = 1.074 \cdot 10^{-2}$). The four way interaction between condition, language, frequency band and ROI ($W(24) = 255.436$, $p < .001$, $R^2 = 1.478 \cdot 10^{-1}$) was also significant.

At fronto-polar electrode sides, in the delta band, TF power was higher for the repetition condition compared to the control condition ($z = 4.232$, $p < .001$, $d = 0.346$), but no effect was found for the TL condition ($z < 1$, $p = .980$) for the German group. For the English group, no effect of condition was found ($W(2) < 1$, $p = .714$). In the theta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 7.424$, $p < .001$, $d = 0.495$; TL - control: $z = 7.152$, $p < .001$, $d = 0.477$) for the German group. For the English group, no effect of condition was found ($W(2) < 1$, $p =.878$). In the alpha band, no differences in power were found for the German group, neither for the repetition compared to the control condition ($z = 1.481$, $p = .277$) nor for the TL compared to the control condition ($z = -1.248$, $p =.424$). For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 6.073$, $p < .001$, $d = 0.351$; TL - control: $z = 6.285$, $p < .001$, $d = 0.363$). In the beta band, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -4.801$, $p < .001$, $d = 0.143$; TL - control: $z =$

- 12.788, $p < .001$, $d = 0.381$) for the German group. For the English group, power was higher for the TL compared to the control condition ($z = 4.051$, $p < .001$, $d = 0.121$), but no effect was found for the repetition condition ($z = 1.125$, $p = .522$). In the gamma band, power was higher for the repetition condition compared to the control condition ($z = 2.811$, $p = .010$, $d = 0.046$) for the German group. No effect was found for the TL condition ($z < 1$, $p = 1.000$). For the English group, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -9.168$, $p < .001$, $d = 0.150$; TL - control: $z = -8.446$, $p < .001$, $d = 0.138$).

At fronto-central electrode sites, in the delta band, TF power was higher for the repetition condition compared to the control condition ($z = 4.127$, $p < .001$, $d = 0.377$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$) for the German group. For the English group, no difference in power was found for either the repetition compared to the control condition ($z = -1.900$, $p = .115$) or the TL compared to the control condition ($z < 1$, $p = .871$). In the theta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.934$, $p < .001$, $d = 0.368$; TL - control: $z = 6.322$, $p < .001$, $d = 0.471$) for the German group. For the English group, power was higher in the TL compared to the control condition ($z = 3.026$, $p = .005$, $d = 0.226$), but no effect was found for the repetition priming condition ($z = 1.435$, $p = .302$). In the alpha band, no effect of condition ($W(2) < 1$, $p = .722$) was found for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 7.889$, $p < .001$, $d = 0.509$; TL - control: $z = 8.403$, $p < .001$, $d = 0.542$). In the beta band, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -3.486$, $p < .001$, $d = 0.116$; TL - control: $z = -12.539$, $p < .001$, $d = 0.418$) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 8.271$, $p < .001$, $d = 0.276$; TL - control: $z = 5.982$, $p < .001$, $d = 0.199$). In the gamma band, power for the TL condition was reduced compared to the control condition ($z = -8.661$, $p < .001$, $d = 0.158$) for the German group, but no effect of repetition priming ($z < 1$, $p = 1.000$) was found. For the English group, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -17.522$, $p < .001$, $d = 0.320$; TL - control: $z = -9.837$, $p < .001$, $d = 0.180$).

At centro-parietal electrode sites, in the delta band, power was reduced for the TL compared to the control condition ($z = -6.558$, $p < .001$, $d = 0.599$), but no effect was found for the repetition compared to the control condition ($z = 1.060$, $p = .578$) for the German group. For the English group, power was reduced for the repetition compared to the control condition ($z =$

-2.113, p = .069, d = 0.193) and enhanced for the TL compared to the control condition (z = 2.412, p = .032, d = 0.220). In the theta band, power was higher for the repetition compared to the control condition (z = 2.508, p = .024, d = 0.187), but no effect was found for the TL compared to the control condition (z < 1, p = .834) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: z = 3.087, p = .004, d = 0.230; TL - control: z = 4.611, p < .001, d = 0.344). In the alpha band, no difference in power was found for either the repetition compared to the control condition (z = 1.362, p = .346) or the TL compared to the control condition (z = -1.686, p = .184) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: z = 9.405, p < .001, d = 0.607; TL - control: z = 9.319, p < .001, d = 0.602). In the beta band, power was reduced for both primed conditions compared to the control condition (repetition - control: z = -2.437, p = .030, d = 0.081; TL - control: z = -8.537, p < .001, d = 0.285) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: z = 5.652, p < .001, d = 0.188; TL - control: z = 5.265, p < .001, d = 0.176). In the gamma band, no effect of condition was found for the German group (W(2) = 4.124, p = .127). For the English group, power was reduced in the repetition compared to the control condition (z = -16.610, p < .001, d = 0.303) and enhanced for the TL compared to the control condition (z = 4.047, p < .001, d = 0.074).

At parietal electrode sites, in the delta band, power was reduced for the TL compared to the control condition (z = -6.447, p < .001, d = .679), but no effect was found for the repetition compared to the control condition (z < 1, p = 1.000) for the German group. For the English group, power was higher in TL condition compared to the control condition (z = 4.546, p < .001, d = 0.479), but no effect was found for the repetition condition (z < 1, p = .669). In the theta band, no difference in power was found for either the repetition compared to the control condition (z = 1.656, p = .196) or the TL compared to the control condition (z = -1.933, p = .106) for the German group. For the English group, power was higher in both primed conditions compared to the control condition (repetition - control: z = 2.104, p = .071, d = 0.181; TL - control: z = 5.472, p < .001, d = 0.471). In the alpha band, power was reduced for the TL compared to the control condition (z = -3.313, p = .002, d = 0.082), but no effect was found for the repetition compared to the control condition (z = 1.095, p = .547) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: z = 5.259, p < .001, d = 0.392; TL - control: z = 4.947, p < .001, d = 0.369). In the beta band, power was reduced for the TL compared to the control condition

(z = -7.600, p < .001, d = 0.293), but no effect was found for the repetition compared to the control condition (z = -1.611, p = .214) for the German group. For the English group, power was higher in both primed conditions compared to the control condition (repetition - control: z = 3.743, p < .001, d = 0.144; TL - control: z = 6.009, p < .001, d = 0.231). In the gamma band, power was higher for the repetition compared to the control condition (z = 7.287, p < .001, d = 0.154), but not for the TL compared to the control condition (z < 1, p = .988) for the German group. For the English group, power was reduced for both primed conditions compared to the control condition (repetition - control: z = -20.575, p < .001, d = 0.434; TL - control: z = -11.803, p < .001, d = 0.249).

For the N400 time window, main effects of condition ($W(2)$ = 154.563, p < .001, $R^2 = 4.383 \cdot 10^{-4}$), frequency band ($W(4)$ = 52,882.730, p < .001, $R^2 = 1.500 \cdot 10^{-1}$) and of ROI ($W(3)$ = 3,507.680, p < .001, $R^2 = 9.946 \cdot 10^{-3}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24)$ = 168.967, p < .001, $R^2 = 1.787 \cdot 10^{-1}$) was also significant. At fronto-polar electrode sites, in the delta band, power was higher for the repetition condition compared to the control condition (z = 3.366, p = 0.002, d = 0.194) for both groups, but no effect was found for TL priming (z = 1.537, p = .248). In the theta band, power was higher in both primed conditions compared to the control condition (repetition - control: z = 4.318, p < .001, d = 0.288; TL - control: z = 2.552, p = .021, d = 0.170) for the German group. For the English group, no effect of condition was found ($W(2)$ < 1, p = .878). In the alpha band, power was reduced in both primed conditions compared to the control condition (repetition - control: z = -5.081, p < .001, d = 0.293; TL - control: z = -4.213, p < .001, d = 0.243) for the German group. For the English group, power was reduced for the repetition condition compared to the control condition (z = -4.726, p < .001, d = 0.273) and higher in the TL condition than in the control condition (z = 5.012, p < .001, d = 0.289). In the beta band, power was higher in the repetition compared to the control condition (z = 9.884, p < .001, d = 0.295) and lower in the TL condition compared to the control condition (z = -4.662, p < .001, d = 0.139) for the German group. For the English group, power was reduced in both primed conditions compared to the control condition (repetition - control: z = -4.939, p < .001, d = 0.147; TL - control: z = -2.725, p = .013, d = 0.081). In the gamma band, power was higher for the repetition compared to the control condition (z = 16.686, p < .001, d = 0.273), but no effect was found for the TL compared to the control condition (z < 1, p = 1.000) for the German group. For the English group, power was reduced in both primed conditions compared to the control condition (repetition - control: z = -5.425, p < .001, d = 0.089; TL - control: z = -15.119, p < .001, d = 0.247).

At fronto-central electrode sites, in the delta band, power was higher for the repetition compared to the control condition (z = 2.866, p = .008, d = 0.262) for the German group. No effect was found for TL priming (z < 1, p = 1.000). For the English group, no effect of condition (W(2) = 2.429, p = .297) was found. In the theta band, power was higher in both primed conditions compared to the control condition (repetition - control: z = 4.154, p < .001, d = 0.310; TL - control: z = 2.108, p = .070, d = 0.157) for the German group. For the English group, a similar pattern was found (repetition - control: z = 1.996, p = .092, d = 0.149; TL - control: z = 8.998, p < .001, d = 0.671). In the alpha band, power was reduced in both primed conditions compared to the control condition (repetition - control: z = -7.482, p < .001, d = 0.483; TL - control: z = -4.726, p < .001, d = 0.305) for the German group. For the English group, power in the TL condition was higher than in the control condition (z = 5.927, p < .001, d = 0.383), but no effect was found for repetition priming (z < 1, p = 1.000). In the beta band, power was higher for the repetition condition compared to the control condition (z = 4.326, p < .001, d = 0.144) and lower in the TL compared to the control condition (z = -6.367, p < .001, d = 0.212) for the German group. For the English group, power in the repetition condition was reduced compared to the control condition (z = -3.567, p < .001, d = 0.119), but no effect of TL priming was found (z = 1.603, p = .218). In the gamma band, power in the repetition condition was higher than in the control condition (z = 4.478, p < .001, d = 0.082) and lower in the TL compared to the control condition (z = -8.393, p < .001, d = 0.153) for the German group. For the English group, power was reduced in both primed conditions compared to the control condition (repetition - control: z = -6.660, p < .001, d = 0.122; TL - control: z = -7.633, p < .001, d = 0.139).

At centro-parietal electrode sites, in the delta band, power was reduced for the TL condition compared to the control condition (z = -2.600, p = .019, d = 0.237), but not for the repetition compared to the control condition (z < 1, p = 1.000) for the German group. For the English group, no effect of condition was found (W(2) < 1, p = .709). In the theta band, no effect was found for the German group (W(2) = 2.077, p = .354). For the English group, power was higher in both primed conditions compared to the control condition (repetition - control: z = 6.395, p < .001, d = 0.477; TL - control: z = 9.185, p < .001, d = 0.685). In the alpha band, no difference in power was found for either the repetition compared to the control condition (z = 1.362, p = .346) or the TL compared to the control condition (z = -1.686, p = .184) for the German group. For the English group, power was higher in both primed conditions compared to the control condition (repetition - control: z = 9.405, p < .001, d = 0.607; TL - control: z = 9.319, p < .001, d = 0.602). In the beta band, power was higher for the repetition compared to the control condition (z = 4.459, p < .001, d = 0.149) and reduced for the TL condition compared to the control condition ($z = -7.206, p < .001, d = 0.240$) for the German group. For the English group, power was higher for the TL compared to the control condition ($z = 3.991, p < .001, d = 0.133$), but no effect was found for the repetition condition ($z = -1.669, p = .190$). In the gamma band, power was higher for the repetition compared to the control condition ($z = 2.593, p = .019, d = 0.047$) and reduced for the TL condition compared to the control condition ($z = -9.958, p < .001, d = 0.182$) for the German group. For the English group, power was reduced for the repetition condition ($z = -13.475, p < .001, d = 0.246$), but no effect was found for TL priming ($z < 1, p = .938$).

At parietal electrode sites, in the delta band, no effects were found. In the theta band, no effect of condition ($W(2) < 1, p = .858$) were found for the German group. For the English group, power in both primed conditions was higher compared to the control condition (repetition - control: $z = 4.913, p < .001, d = 0.423$; TL - control: $z = 7.089, p < .001, d = 0.610$). In the alpha band, power in both primed conditions was lower compared to the control condition (repetition - control: $z = -3.869, p < .001, d = 0.288$; TL - control: $z = -5.891, p < .001, d = 0.439$) for the German group. For the English group, power in both primed conditions was higher compared to the control condition (repetition - control: $z = 4.490, p < .001, d = 0.335$; TL - control: $z = 3.939, p < .001, d = 0.294$). In the beta band, power was higher for the repetition compared to the control condition ($z = 2.997, p = .006, d = 0.115$) and lower in the TL compared to the control condition ($z = -10.867, p < .001, d = 0.418$) for the German group. For the English group, power was higher in the TL compared to the control condition ($z = 3.594, p < .001, d = 0.138$), but no effect was found for the repetition condition ($z < 1, p = .965$). In the gamma band, power was higher for the repetition compared to the control condition ($z = 6.510, p < .001, d = 0.137$) and lower in the TL compared to the control condition ($z = -8.936, p < .001, d = 0.188$) for the German group. For the English group, power in both primed conditions was reduced compared to the control condition (repetition - control: $z = -15.427, p < .001, d = 0.325$; TL - control: $z = -8.954, p < .001, d = 0.189$).

For a prime duration of 50.00 ms, a main effect of condition ($W(2) = 89.614, p < .001, R^2 = 1.342 \cdot 10^{-4}$), time window ($W(1) = 2{,}194.577, p < .001, R^2 = 3.400 \cdot 10^{-3}$), frequency band ($W(4) = 93{,}667.169, p < .001, R^2 = 1.451 \cdot 10^{-1}$) and ROI ($W(3) = 1{,}419.767, p < .001, R^2 = 2.199 \cdot 10^{-3}$). The five-way interaction between condition, language, time window, frequency band and ROI ($W(24) = 57.673, p < .001, R^2 = 2.000 \cdot 10^{-1}$) was also significant. For the N250 time window, a main effect of condition ($W(2) = 148.530, p < .001, R^2 = 4.982 \cdot 10^{-4}$), frequency band ($W(4) = 38{,}152.747, p < .001, R^2 = 1.280 \cdot 10^{-1}$) and ROI ($W(3) = 755.251, p < .001, R^2 =$

$2.533 \cdot 10^{-3}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 221.937$, $p < .001$, $R^2 = 1.481 \cdot 10^{-1}$) was also significant.

At fronto-polar electrode sites, in the delta band, power was higher for the TL compared to the control condition ($z = 3.322$, $p = .002$, $d = 0.271$), but no effect was found for repetition priming ($z < 1$, $p = 1.000$) for the German group. For the English group, power in both primed conditions was higher compared to the control condition (repetition - control: $z = 2.698$, $p = .014$, $d = 0.220$; TL - control: $z = 10.296$, $p < .001$, $d = 0.841$). In the theta band, power was lower for the repetition compared to the control condition ($z = -3.793$, $p < .001$, $d = 0.253$), but no effect was found for TL priming ($z = 1.634$, $p = .205$) for the German group. For the English group, power was higher in the TL condition than in the control condition ($z = 4.920$, $p < .001$, $d = 0.328$), but no effect was found for the repetition condition ($z < 1$, $p = .987$). In the alpha band, power was higher for the TL compared to the control condition ($z = 6.229$, $p < .001$, $d = 0.360$), but no effect was found for repetition priming ($z = -1.403$, $p = .321$) for the German group. For the English group, no effect of condition was found ($W(2) = 1.393$, $p = .498$). In the beta band, power for both primed conditions was lower compared to the control condition (repetition - control: $z = -6.994$, $p < .001$, $d = 0.209$; TL - control: $z = -6.153$, $p < .001$, $d = 0.183$) for the German group. For the English group, power for both primed conditions was higher compared to the control condition (repetition - control: $z = 9.770$, $p < .001$, $d = 0.291$; TL - control: $z = 3.829$, $p < .001$, $d = 0.114$). In the gamma band, power was reduced for the repetition compared to the control condition ($z = -4.843$, $p < .001$, $d = 0.079$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$) for the German group. For the English group, power in both primed condition was higher than in the control condition (repetition - control: $z = 9.171$, $p < .001$, $d = 0.150$; TL - control: $z = 4.593$, $p < .001$, $d = 0.075$).

At fronto-central electrode sites, in delta band, power was higher for the TL compared to the control condition ($z = 4.219$, $p < .001$, $d = 0.385$), but no effect was found for repetition priming ($z = 1.342$, $p = .360$) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.143$, $p = .064$, $d = 0.196$; TL - control: $z = 10.137$, $p < .001$, $d = 0.925$). In the theta band, power was marginally lower for the repetition compared to the control condition ($z = -2.006$, $p = .090$, $d = .106$) and higher for the TL compared to the control condition ($z = 5.011$, $p < .001$, $d = 0.264$) for both groups. In the alpha band, power was higher in the TL compared to the control condition ($z = 6.605$, $p < .001$, $d = 0.426$), but not effect was found for the repetition condition ($z < 1$, $p = .989$) for the German group. For the English group, power was reduced in the TL condition compared to the control condition ($z = -2.705$, $p = .014$, $d = 0.175$), but no effect was found for the repetition condition ($z < 1$, $p = .642$). In the beta band, power for both primed conditions was lower compared to the control condition (repetition - control: $z = -4.844$, $p < .001$, $d = 0.162$; TL - control: $z = -3.924$, $p < .001$, $d = 0.131$) for the German group. For the English group, power for both primed conditions was higher compared to the control condition (repetition - control: $z = 12.840$, $p < .001$, $d = 0.428$; TL - control: $z = 8.257$, $p < .001$, $d = 0.275$). In the gamma band, power for both primed conditions was reduced compared to the control condition (repetition - control: $z = -13.998$, $p < .001$, $d = 0.256$; TL - control: $z = -4.193$, $p < .001$, $d = 0.077$) for the German group. For the English group, power in the repetition condition was higher compared to the control condition ($z = 7.676$, $p < .001$, $d = 0.140$), but no effect of TL priming was found ($z < 1$, $p = 1.000$).

At centro-parietal electrode sites, in the delta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.573$, $p < .001$, $d = 0.326$; TL - control: $z = 4.356$, $p < .001$, $d = 0.398$) for the German group. For the English group, power was higher for the TL compared to the control condition ($z = 5.082$, $p < .001$, $d = 0.464$), but no effect was found for the repetition condition ($z = -1.271$, $p = .407$). In the theta band, power was higher for the TL compared to the control condition ($z = 5.915$, $p < .001$, $d = 0.441$), but no effect was found for the repetition condition ($z < 1$, $p = 1.000$) for the German group. For the English group, a similar pattern was found (repetition - control: $z < 1$, $p = 1.000$; TL - control: $z = 2.967$, $p = .006$, $d = 0.221$). In the alpha band, power was higher for the TL compared to the control condition ($z = 6.832$, $p < .001$, $d = 0.441$), but no effect was found for the repetition condition ($z = 1.404$, $p = .321$) for the German group. For the English group, power was higher for the repetition compared to the control condition ($z = 2.603$, $p = .019$, $d = 0.168$) and lower for the TL compared to the control condition ($z = -3.267$, $p = .002$, $d = 0.211$). In the beta band, power was higher for the TL compared to the control condition ($z = 3.062$, $p = .004$, $d = 0.102$), but no effect was found for the repetition condition ($z = -1.341$, $p = .360$) for the German group. For the English group, power for both primed conditions was higher compared to the control condition (repetition - control: $z = 10.024$, $p < .001$, $d = 0.334$; TL - control: $z = 7.318$, $p < .001$, $d = 0.244$). In the gamma band, power for both primed conditions was reduced compared to the control condition (repetition - control: $z = -12.432$, $p < .001$, $d = 0.227$; TL - control: $z = -9.526$, $p < .001$, $d = 0.174$) for the German group. For the English group, power for both primed conditions was enhanced compared to the control condition (repetition - control: $z = 9.933$, $p < .001$, $d = 0.181$; TL - control: $z = 11.636$, $p < .001$, $d = 0.212$).

At parietal electrode sites, in the delta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.624$, $p < .001$, $d = 0.382$; TL - control: $z = 4.537$, $p < .001$, $d = 0.478$) for the German group. For the English group, no effect on power was found for either the TL compared to the control condition ($z = 1.713$, $p =.173$) or for the repetition compared to the control condition ($z < 1$, $p = .665$). In the theta band, power was higher for the TL compared to the control condition ($z = 6.546$, $p < .001$, $d = 0.563$), but no effect was found for the repetition condition ($z < 1$, $p = .825$) for the German group. For the English group, no effect of condition was found ($W(2) = 2.141$, $p = .343$). In the alpha band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.157$, $p = .003$, $d = 0.235$; TL - control: $z = 7.668$, $p < .001$, $d = 0.572$) for the German group. For the English group, power was higher for the repetition compared to the control condition ($z = 2.678$, $p = .015$, $d = 0.200$) and lower for the TL compared to the control condition ($z = -3.135$, $p = .003$, $d = 0.234$). In the beta band, power was higher for the TL compared to the control condition ($z = 5.674$, $p < .001$, $d = 0.218$), but no effect was found for the repetition condition ($z = -1.351$, $p = .353$) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 6.458$, $p < .001$, $d = 0.249$; TL - control: $z = 4.192$, $p < .001$, $d = 0.161$). In the gamma band, power for both primed conditions was reduced compared to the control condition (repetition - control: $z = -11.654$, $p < .001$, $d = 0.246$; TL - control: $z = -6.805$, $p < .001$, $d = 0.143$) for the German group. For the English group, power for both primed conditions was enhanced compared to the control condition (repetition - control: $z = 4.594$, $p < .001$, $d = 0.097$; TL - control: $z = 7.623$, $p < .001$, $d = 0.161$).

For the N400 time window, main effects of condition ($W(2) = 263.022$, $p < .001$, $R^2 = 7.370 \cdot 10^{-4}$), frequency band ($W(4) = 74{,}938.801$, $p < .001$, $R^2 = 2.100 \cdot 10^{-1}$), and ROI ($W(3) = 761.660$, $p < .001$, $R^2 = 2.134 \cdot 10^{-3}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 81.010$, $p < .001$, $R^2 = 2.371 \cdot 10^{-1}$) was also significant. At fronto-polar electrode sites, in the delta band, no effect of condition ($W(2) = 1.313$, $p = .519$) was found for the German group. For the English group, power was reduced for the repetition compared to the control condition ($z = -6.181$, $p < .001$, $d = 0.505$) and enhanced in the TL compared to the control condition ($z = 5.613$, $p < .001$, $d = 0.458$). In the theta band, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -3.745$, $p < .001$, $d = 0.250$; TL - control: $z = -2.844$, $p = .009$, $d = 0.190$) for the German group. For the English group, power was reduced for the repetition compared to the control condition ($z = -5.534$, $p < .001$, $d = 0.369$) and enhanced for the TL compared to the control condition (*z* = 2.888, *p* = .008, *d* = 0.193). In the alpha band, power was reduced for the repetition compared to the control condition (*z* = -8.488, *p* < .001, *d* = 0.490) and higher in the TL compared to the control condition (*z* = 3.384, *p* = .001, *d* = 0.195) for the German group. For the English group, power was reduced for the repetition condition compared to the control condition (*z* = -5.243, *p* < .001, *d* = 0.303), but no effect was found for the TL condition (*z* = -1.193, *p* = .466). In the beta band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -5.027, *p* = .003, *d* = 0.150; TL - control: *z* = -4.810, *p* < .001, *d* = 0.143) for the German group. For the English group, power was higher in the repetition compared to the control condition (*z* = 4.324, *p* < .001, *d* = 0.129), but no effect was found for the TL condition (*z* < 1, *p* = 1.000). In the gamma band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -16.157, *p* < .001, *d* = 0.264; TL - control: *z* = -15.129, *p* < .001, *d* = 0.247) for the German group. For the English group, power was reduced for the TL condition compared to the control condition (*z* = -12.227, *p* < .001, *d* = 0.200), but no effect was found for the repetition condition (*z* = -1.491, *p* = .272).

At fronto-central electrode sites, in the delta band, no effect of condition (*W*(2) < 1, *p* = .669) was found for the German group. For the English group, power was reduced for the repetition compared to the control condition (*z* = -4.665, *p* < .001, *d* = 0.426) and enhanced for the TL compared to the control condition (*z* = 5.671, *p* < .001, *d* = 0.518). In the theta band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -3.115, *p* = .004, *d* = 0.232; TL - control: *z* = -2.248, *p* = .049, *d* = 0.168) for the German group. For the English group, power was reduced for the repetition condition (z = - 5.126, *p* < .001, *d* = 0.382), but no effect was found for the TL condition (*z* = 1.480, *p* = .278). In the alpha band, power was reduced for the repetition compared to the control condition (*z* = -4.820, *p* < .001, *d* = 0.311) and enhanced for the TL compared to the control condition (*z* = 2.383, *p* = .034, *d* = 0.154) for the German group. For the English group, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -4.619, *p* < .001, *d* = 0.298; TL - control: *z* = -2.709, *p* = .014, *d* = 0.175). In the beta band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -3.341, *p* = .002, *d* = 0.111; TL - control: *z* = -7.799, *p* < .001, *d* = 0.260) for the German group. For the English group, power was higher for both primed conditions compared to the control condition (repetition - control: *z* = 4.948, *p* < .001, *d* = 0.165; TL - control: *z* = 3.457, *p* = .001, *d* = 0.115). In the gamma band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -16.460, *p* < .001, *d* = 0.301; TL - control: *z* = -17.416,

$p < .001$, $d = 0.318$) for the German group. For the English group, power was reduced for the TL compared to the control condition ($z = -7.141$, $p < .001$, $d = 0.130$), but no effect was found for the repetition condition ($z = -1.707$, $p = .176$).

At centro-parietal electrode sites, in the delta band, power was higher for the repetition compared to the control condition ($z = 3.005$, $p = .005$, $d = 0.274$) for the German group. No effect was found for the TL condition ($z = 1.176$, $p = .480$). For the English group, power was reduced in the repetition compared to the control condition ($z = -5.051$, $p < .001$, $d = 0.461$) and enhanced in the TL compared to the control condition ($z = 3.308$, $p = .002$, $d = 0.302$). In the theta band, no effect of condition ($W(2) = 2.009$, $p = .366$) for the German group. For the English group, power was reduced in the repetition compared to the control condition ($z = -4.512$, $p < .001$, $d = 0.336$), but no effect was found for the TL condition ($z = 1.945$, $p = .104$). In the alpha band, power for the German group was higher for the TL compared to the control condition ($z = 6.832$, $p < .001$, $d = 0.441$), but no effect was found for repetition priming ($z = 1.404$, $p = .321$). For the English group, power was higher in the repetition compared to the control condition ($z = 2.603$, $p = .019$, $d = 0.168$) and reduced in the TL compared to the control condition ($z = -3.267$, $p = .002$, $d = 0.211$). In the beta band, power was higher for the repetition compared to the control condition ($z = 2.386$, $p = .034$, $d = 0.080$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$) for the German group. For the English group, a similar pattern was found (repetition - control: $z = 4.995$, $p < .001$, $d = 0.167$; TL - control: $z < 1$, $p = 1.000$). In the gamma band, power was reduced for both primed conditions compared to the control condition (repetition - control: $z = -14.675$, $p < .001$, $d = 0.268$; TL - control: $z = -12.494$, $p < .001$, $d = 0.228$) for the German group. For the English group, no effect of condition was found ($W(2) = 3.937$, $p =.140$).

At parietal electrode sites, in the delta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.392$, $p < .001$, $d = 0.463$; TL - control: $z = 2.849$, $p = .009$, $d = 0.300$) for the German group. For the English group, power was reduced for the repetition condition compared to the control condition ($z = -3.127$, $p = .004$, $d = 0.330$) but not for the TL compared to the control condition ($z = 1.565$, $p =.235$). In the theta band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.307$, $p = .042$, $d = 0.199$; TL - control: $z = 3.666$, $p < .001$, $d = 0.315$) for the German group. For the English group, power was reduced in the repetition compared to the control condition ($z = -2.016$, $p = .088$, $d = 0.174$) and higher in the TL compared to the control condition ($z = 2.801$, $p = .010$, $d = 0.241$). In the alpha band, power was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.623$, $p < .001$, *d* = 0.345; TL - control: *z* = 6.928, *p* < .001, *d* = 0.516) for the German group. For the English group, no difference in power was found for either the repetition compared to the control condition (*z* = -1.783, *p* = .149) or for the TL compared to the control condition (*z* < 1, *p* = 1.000). In the beta band, power was higher for both primed conditions compared to the control condition (repetition - control: *z* = 8.053, *p* < .001, *d* = 0.310; TL - control: *z* = 4.008, *p* < .001, *d* = 0.154) for the German group. For the English group, power was higher in the repetition compared to the control condition (*z* = 5.384, *p* < .001, *d* = 0.207), but not for the TL compared to the control condition (*z* < 1, *p* = 1.000). In the gamma band, power was reduced for both primed conditions compared to the control condition (repetition - control: *z* = -11.803, *p* < .001, *d* = 0.176; TL - control: *z* = -9.162, *p* < .001, *d* = 0.137) for both groups.

ITPC. The overall model showed a main effect of condition (*W*(2) = 157.520, *p* < .001, $R^2 = 1.216 \cdot 10^{-4}$), time window (*W*(1) = 1,760.000, *p* < .001, $R^2 = 1.358 \cdot 10^{-2}$), frequency band (*W*(4) = 272,580.000, *p* < .001, $R^2 = 2.104 \cdot 10^{-1}$) and ROI (*W*(3) = 230.530, *p* < .001, $R^2 = 1.779 \cdot 10^{-4}$). The six-way interaction between condition, language, frequency band, time window, ROI and prime duration (*W*(24) = 259.760, *p* < .001, $R^2 = 3.335 \cdot 10^{-1}$) also reached significance. Subsequent analyses by prime duration showed for a duration of 66.67 ms, a main effect of condition (*W*(2) = 171.970, *p* < .001, $R^2 = 2.518 \cdot 10^{-4}$), time window (*W*(1) = 8,402.900, *p* < .001, $R^2 = 1.230 \cdot 10^{-2}$), frequency band (*W*(4) = 161,310.000, *p* < .001, $R^2 = 2.362 \cdot 10^{-1}$) and ROI (*W*(3) = 129.760, *p* < .001, $R^2 = 1.900 \cdot 10^{-4}$) the five-way interaction between condition, language, frequency band, time window and ROI (*W*(24) = 125.780, *p* < .001, $R^2 = 3.683 \cdot 10^{-1}$) was also significant. Subsequent analyses by time window showed for the N250 time window a main effect of condition (*W*(2) = 72.360, *p* < .001, $R^2 = 1.853 \cdot 10^{-4}$), frequency band (*W*(4) = 165,130.000, *p* < .001, $R^2 = 4.229 \cdot 10^{-1}$) and ROI (*W*(3) = 254.680, *p* < .001, $R^2 = 6.522 \cdot 10^{-4}$). The four-way interaction between condition, language, frequency band and ROI (*W*(24) = 249.760, *p* < .001, $R^2 = 4.382 \cdot 10^{-1}$) also reached significance.

At fronto-polar electrode sites, in the delta band, no significant effects were found. In the theta band, ITPC was higher for the TL compared to the control condition (*z* = 4.218, *p* < .001, *d* = 0.281), but not for the repetition compared to the control condition (*z* = -1.640, *p* = .202) for the German group. For the English group, ITPC was reduced in the repetition compared to the control condition (*z* = -6.590, *p* < .001, *d* = 0.439), but no effect was found for the TL condition (*z* < 1, *p* = .705). In the alpha band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: *z* = 4.421, *p* < .001, *d* = 0.255; TL - control: *z* = 2.535, *p* = .023, *d* = 0.146) for the German group. For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: z = -2.383, p = .034, d = 0.138; TL - control: z = -4.889, p < .001, d = 0.282). In the beta band, no effect of condition was found for the German group (W(2) = 2.131, p = .345). For the English group, ITPC was reduced for the repetition compared to the control condition (z = -6.955, p < .001, d = 0.207) and higher for the TL compared to the control condition (z = 2.249, p = .049, d = 0.067). In the gamma band, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: z = -7.053, p < .001, d = 0.115; TL - control: z = -8.974, p < .001, d = 0.147) for the German group. For the English group, ITPC was lower for the repetition compared to the control condition (z = -5.305, p < .001, d = 0.087), but no effect was found for the TL condition (z < 1, p = .989).

At fronto-central electrode sites, in the delta band, ITPC for both groups was higher for the TL condition compared to the control condition (z = 2.827, p = .009, d = 0.183), but no effect of repetition priming (z < 1, p = 1.000) was found. In the theta band, ITPC for the TL condition was higher compared to the control condition (z = 3.534, p < .001, d = 0.263), but no effect of repetition priming (z = -1.824, p = .136) was found for the German group. For the English group, ITPC was lower for the repetition condition compared to the control condition (z = -5.955, p < .001, d = 0.444), but no effect of TL priming was found (z < 1, p = 1.000). In the alpha band, ITPC was enhanced for both primed conditions compared to the control condition (repetition - control: z = 5.525, p < .001, d = 0.357; TL - control: z = 3.243, p = .002, d = 0.209) for the German group. For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: z = -2.891, p = .008, d = 0.187; TL - control: z = -2.290, p = .044, d = 0.148). In the beta band, ITPC was higher for the repetition than for the control condition (z = 2.297, p = .043, d = 0.077) for the German group. No effect was found for the TL compared to the control condition (z = -1.496, p = .269). For the English group, ITPC was reduced for the repetition compared to the control condition (z = -7.323, p < .001, d = 0.244), but no effect of TL priming was found (z < 1, p = 1.000). In the gamma band, no effect of condition was found for the German group (W(2) = 2.446, p = .294). For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: z = -2.572, p = .020, d = 0.047; TL - control: z = -2.439, p = .030, d = 0.045).

At centro-parietal electrode sites, in the delta band, ITPC for the German group was reduced for the repetition compared to the control condition (z = -3.810, p < .001, d = 0.348), but no effect was found for the TL compared to the control condition (z < 1, p = 1.000). For the English group, no effect of condition (W(2) < 1, p = .643) was found. In the theta band, ITPC was lower for the repetition compared to the control condition (*z* = -4.906, *p* < .001, *d* = 0.366) and higher for the TL compared to the control condition (*z* = 2.218, *p* = .053, *d* = 0.165) for the German group. For the English group, no effect of condition was found (*W*(2) = 3.978, *p* = .137). In the alpha band, no effect of condition (*W*(2) < 1, *p* = .921) was found for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition (*z* = -3.297, *p* = .002, *d* = 0.213), but no effect was found for TL priming (*z* = 1.242, *p* = .429). In the beta band, ITPC for the German group was lower for the TL compared to the control condition (*z* = -9.112, *p* < .001, *d* = 0.304), but not for the repetition compared to the control condition (*z* = -1.035, *p* = .601). For the English group, ITPC was reduced for the repetition compared to the control condition (*z* = -6.454, *p* < .001, *d* = 0.215), but not for the TL compared to the control condition (*z* = -1.118, *p* = .527). In the gamma band, ITPC was higher for the repetition compared to the control condition (*z* = 2.507, *p* = .024, *d* = 0.046), but no effect was found for the TL compared to the control condition (*z* < 1, *p* = .883) for the German group. For the English group, ITPC was reduced for the TL compared to the control condition (*z* = -5.400, *p* < .001, *d* = 0.099), but not for the repetition compared to the control condition (*z* = -1.466, *p* = .285).

At parietal electrode sites, in the delta band, ITPC was reduced for the repetition compared to the control condition (*z* = -4.253, *p* < .001, *d* = 0.448) for the German group. No effect was found for TL priming (*z* = -1.839, *p* = .132). For the English group, ITPC was marginally higher for the repetition compared to the control condition (*z* = 2.115, *p* = .069, *d* = 0.223), but no effect was found for the TL compared to the control condition (*z* = 1.622, *p* = .210). In the theta band, ITPC for the German group was reduced for the repetition compared to the control condition (*z* = -3.284, *p* = .002, *d* = 0.283), but no effect was found for TL priming (*z* < 1, *p* = 1.000). For the English group, ITPC was higher for the TL compared to the control condition (*z* = 3.314, *p* = .002, *d* = 0.285), but no effect was found for the repetition compared to the control condition (*z* = 1.446, *p* = .296). In the alpha band, no effect of condition was found for the German group (*W*(2) = 3.077, *p* = .215). For the English group, ITPC was reduced for the repetition compared to the control condition (*z* = -2.278, *p* = .045, *d* = 0.170) and higher for the TL compared to the control condition (*z* = 3.438, *p* = .001, *d* = 0.256). In the beta band, ITPC was reduced for the TL compared to the control condition (*z* = -6.458, *p* < .001, *d* = 0.249), but no effect was found for repetition priming (*z* = -1.790, *p* = .147) for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition (*z* = -4.385, *p* < .001, *d* = 0.169) and higher for the TL compared to the control condition (*z* = 5.405, *p* < .001, *d* = 0.208). In the gamma band, ITPC for both groups was higher in the repetition compared to the control condition (z = 4.441, p < .001, d = 0.066) and marginally lower in the TL compared to the control condition (z = -2.119, p = .068, d = 0.032).

For the N400 time window, main effects of condition ($W(2)$ = 309.641, p < .001, R^2 = $1.289 \cdot 10^{-3}$), frequency band ($W(4)$ = 19,819.619, p < .001, R^2 = $5.255 \cdot 10^{-2}$), and ROI ($W(24)$ = 30.403, p < .001, R^2 = $1.266 \cdot 10^{-4}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24)$ = 252.299, p < .001, R^2 = $1.052 \cdot 10^{-1}$) was also significant. At fronto-polar electrode sites, in the delta band, ITPC was higher for the TL compared to the control condition (z = 4.368, p < .001, d = 0.357), but no effect was found for repetition priming (z = -1.469, p = .284) for the German group. For the English group, ITPC for both primed conditions was higher compared to the control condition (repetition - control: z = 2.630, p = .017, d = 0.215; TL - control: z = 6.094, p < .001, d = 0.498). In the theta band, ITPC was reduced for the repetition compared to the control condition (z = -2.708, p = .014, d = 0.181), but no effect was found for TL priming (z = 1.949, p = .103) for the German group. For the English group, a similar pattern was observed (repetition - control: z = -6.590, p < .001, d = 0.439; TL - control: z < 1, p = .705). In the alpha band, no effect of condition was found for the German group ($W(2)$ < 1, p = .710). For the English group, ITPC was higher for the TL compared to the control condition (z = 8.716, p < .001, d = 0.503), but no effect was found for repetition priming (z < 1, p = 1.000). In the beta band, ITPC was reduced for the repetition compared to the control condition (z = -2.726, p = .013, d = 0.081), but no effect was found for TL priming (z < 1, p = .947) for the German group. For the English group, ITPC was marginally higher for the repetition compared to the control condition (z = 1.990, p = .093, d = 0.059), but no effect was found for the TL condition (z < 1, p = 1.000). In the gamma band, no effect of condition was found for the German group ($W(2)$ = 1.840, p = .399). For the English group, ITPC was reduced for the repetition compared to the control condition (z = -5.941, p < .001, d = 0.097) and higher for the TL compared to the control condition (z = 2.513, p = .024, d = 0.041).

At fronto-central electrode sites, in the delta band, no effect of condition was found for the German group ($W(2)$ = 2.425, p = .298). For the English group, ITPC was higher for the TL compared to the control condition (z = 5.844, p < .001, d = 0.534), but not for the repetition compared to the control condition (z = 1.301, p = .387). In the theta band, ITPC was reduced for the repetition compared to the control condition (z = -2.425, p = .031, d = 0.181), but no effect was found for the TL condition (z = 1.059, p = .579) for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition (z = -3.488, p = .001, d = 0.260), and higher for the TL condition compared to the control condition ($z = 3.427$, $p = .001$, $d = 0.255$). In the alpha band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.921$, $p = .007$, $d = 0.189$; TL - control: $z = 2.753$, $p = .012$, $d = 0.178$) for the German group. For the English group, ITPC was higher for the TL compared to the control condition ($z = 7.634$, $p < .001$, $d = 0.493$), but not for the repetition compared to the control condition ($z < 1$, $p = .808$). In the beta band, no difference in ITPC was found for either the repetition compared to the control condition ($z = -1.169$, $p = .485$) or the TL compared to the control condition ($z = 1.265$, $p = .412$) for either of the two groups. In the gamma band, ITPC was higher in the TL compared to the control condition ($z = 2.587$, $p = .019$, $d = 0.033$), but not for the repetition compared to the control condition ($z < 1$, $p = 1.000$) for both groups.

At centro-parietal electrode sites, in the delta band, ITPC was reduced for the repetition compared to the control condition ($z = -5.192$, $p < .001$, $d = 0.474$), but no effect was found for TL priming ($z < 1$, $p = 1.000$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.307$, $p = .002$, $d = 0.302$; TL - control: $z = 2.747$, $p = .012$, $d = 0.251$). In the theta band, ITPC was higher for the TL compared to the control condition ($z = 3.535$, $p < .001$, $d = 0.186$) for both groups. No effect was found for the repetition compared to the control condition ($z = 1.216$, $p = .448$). In the alpha band, no effect of condition was found for the German group ($W(2) < 1$, $p = .921$). For the English group, ITPC was reduced for the repetition compared to the control condition ($z = -3.297$, $p = .002$, $d = 0.213$), but no effect was found for the TL condition ($z = 1.242$, $p = .429$). In the beta band, ITPC was higher for the TL compared to the control condition ($z = 2.580$, $p = .020$, $d = 0.086$), but not for the repetition compared to the control condition ($z = 1.564$, $p = .236$) for the German group. For the English group, no effect of condition was found ($W(2) = 3.722$, $p = .156$). In the gamma band, ITPC for both primed conditions was higher compared to the control condition (repetition - control: $z = 5.495$, $p < .001$, $d = 0.100$; TL - control: $z = 2.879$, $p = .008$, $d = 0.053$) for the German group. For the English group, a similar pattern was found (repetition - control: $z = 2.677$, $p = .015$, $d = 0.049$; TL - control: $z = 6.848$, $p < .001$, $d = 0.125$).

At parietal electrode sites, in the delta band, ITPC was reduced for the repetition compared to the control condition ($z = -3.292$, $p = .002$, $d = 0.347$), but not for the TL compared to the control condition ($z = -1.536$, $p = .249$) for the German group. For the English group, ITPC for both primed conditions was higher compared to the control condition (repetition - control: $z = 3.791$, $p < .001$, $d = 0.400$; TL - control: $z = 3.329$, $p = .002$, $d = 0.351$). In the theta band, no significant effects were found. In the alpha band, ITPC for both primed conditions was higher compared to the control condition (repetition - control: $z = 5.293$, $p < .001$, $d = 0.390$; TL - control: $z = 2.202$, $p = .055$, $d = 0.164$) for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition ($z = -2.749$, $p = .012$, $d = 0.205$) and higher for the TL compared to the control condition ($z = 2.859$, $p = .009$, $d = 0.213$). In the beta band, ITPC for both primed conditions was higher compared to the control condition (repetition - control: $z = 2.626$, $p = .017$, $d = 0.072$; TL - control: $z = 4.561$, $p < .001$, $d = 0.124$) for both groups. In the gamma band, ITPC was higher for the TL compared to the control condition ($z = 2.336$, $p = .039$, $d = 0.049$), but not for the repetition compared to the control condition ($z < 1$, $p = .761$) for the German group. For the English group, ITPC for both primed conditions was higher compared to the control condition (repetition - control: $z = 7.047$, $p < .001$, $d = 0.149$; TL - control: $z = 12.665$, $p < .001$, $d = 0.267$).

For a prime duration of 50.00 ms, a main effect of condition ($W(2) = 56.669$, $p < .001$, $R^2 = 9.276 \cdot 10^{-5}$), time window ($W(1) = 9{,}217.620$, $p < .001$, $R^2 = 1.509 \cdot 10^{-2}$), frequency band ($W(4) = 113{,}127.599$, $p < .001$, $R^2 = 1.852 \cdot 10^{-1}$) and ROI ($W(3) = 102.610$, $p < .001$, $R^2 = 1.680 \cdot 10^{-4}$) were found. The five-way interaction between condition, language, time window, frequency band and ROI ($W(24) = 179.587$, $p < .001$, $R^2 = 2.923 \cdot 10^{-1}$) was also significant. Subsequent analyses by time window showed for the N250 time window, a main effect of condition ($W(2) = 73.507$, $p < .001$, $R^2 = 2.149 \cdot 10^{-4}$), frequency band ($W(4) = 117{,}850.000$, $p < .001$, $R^2 = 3.446 \cdot 10^{-1}$) and ROI ($W(3) = 199.960$, $p < .001$, $R^2 = 5.847 \cdot 10^{-4}$). The four-way interaction between condition, language, frequency band and ROI ($W(24) = 211.490$, $p < .001$, $R^2 = 3.595 \cdot 10^{-1}$) was also significant.

At fronto-polar electrode sites, in the delta band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.803$, $p < .001$, $d = 0.311$; TL - control: $z = 3.670$, $p < .001$, $d = 0.300$) for the German group. For the English group, ITPC was marginally higher for the TL compared to the control condition ($z = 2.022$, $p = .086$, $d = 0.165$), but no effect was found for repetition priming ($z = -1.151$, $p = .500$). In the theta band, no effect of condition was found for the German group ($W(2) = 3.052$, $p = .217$). For the English group, ITPC was higher for the TL condition compared to the control condition ($z = 6.788$, $p < .001$, $d = 0.453$), but no effect was found for the repetition condition ($z = 1.804$, $p = .142$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 3.522$, $p < .001$, $d = 0.203$), but no effect was found for the TL condition ($z = -1.837$, $p = .133$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.316$, $p = .002$, $d = 0.191$; TL - control: $z = 4.433$, $p < .001$, $d = 0.256$). In the beta band, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -7.782$, $p < .001$, $d = 0.232$; TL - control: $z = -7.793$, $p < .001$, $d = 0.232$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.921$, $p < .001$, $d = 0.147$; TL - control: $z = 12.814$, $p < .001$, $d = 0.382$). In the gamma band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 7.682$, $p < .001$, $d = 0.125$; TL - control: $z = 8.819$, $p < .001$, $d = 0.144$) for the German group. For the English group, ITPC was reduced for the TL compared to the control condition ($z = -9.490$, $p < .001$, $d = 0.155$), but not for the repetition compared to the control condition ($z < 1$, $p = 1.000$).

At fronto-central electrode sites, in the delta band, ITPC was higher for the repetition compared to the control condition ($z = 2.709$, $p = .014$, $d = 0.247$), but not for the TL compared to the control condition ($z = 1.068$, $p = .571$) for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition ($z = -2.838$, $p = .009$, $d = 0.259$), but no effect was found for the TL condition ($z = 1.323$, $p = .372$). In the theta band, no difference in ITPC was found for either the repetition compared to the control condition ($z = 1.193$, $p = .466$) or for the TL compared to the control condition ($z = -1.388$, $p = .330$) for the German group. For the English group, ITPC was higher for the TL compared to the control condition ($z = 4.871$, $p < .001$, $d = 0.363$), but no effect was found for the repetition condition ($z < 1$, $p = .956$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 6.684$, $p < .001$, $d = 0.432$), but not for the TL compared to the control condition ($z < 1$, $p = 1.000$) for the German group. For the English group, no effect of condition was found ($W(2) = 1.948$, $p = .378$). In the beta band, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -8.095$, $p < .001$, $d = 0.270$; TL - control: $z = -4.747$, $p < .001$, $d = 0.158$) for the German group. For the English group, ITPC was enhanced for both primed conditions compared to the control condition (repetition - control: $z = 2.861$, $p = .009$, $d = 0.095$; TL - control: $z = 10.272$, $p < .001$, $d = 0.342$). In the gamma band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.590$, $p < .001$, $d = 0.084$; TL - control: $z = 10.792$, $p < .001$, $d = 0.197$) for the German group. For the English group, ITPC was reduced for the TL compared to the control condition ($z = -7.959$, $p < .001$, $d = 0.145$), but no effect was found for the repetition condition ($z = -1.736$, $p = .165$).

At centro-parietal electrode sites, in the delta band, ITPC was higher for the repetition compared to the control condition ($z = 4.415$, $p < .001$, $d = 0.403$), but no effect was found for TL priming ($z = 1.765$, $p = .155$) for the German group. For the English group, ITPC was reduced for the repetition compared to the control condition ($z = -3.444$, $p = .001$, $d = 0.314$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$). In the theta band, no difference in ITPC was found for either of the primed conditions compared to the control condition (repetition - control: $z = 1.954$, $p = .101$; TL - control: $z = -1.369$, $p = .342$) for the German group. For the English group, a similar pattern was observed (repetition - control: $z = -1.937$, $p = .106$; TL - control: $z < 1$, $p = 1.000$). In the alpha band, ITPC was higher for the repetition condition compared to the control condition ($z = 4.556$, $p < .001$, $d = 0.208$) for both groups. No effect of TL priming was found ($z = 1.537$, $p = .249$). In the beta band, ITPC was reduced for the repetition compared to the control condition ($z = -4.432$, $p < .001$, $d = 0.148$), but not for the TL compared to the control condition ($z < 1$, $p = .798$) for the German group. For the English group, ITPC was higher for the TL condition compared to the control condition ($z = 10.037$, $p < .001$, $d = 0.335$), but no effect was found for repetition priming ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the TL compared to the control condition ($z = 5.180$, $p < .001$, $d = 0.095$) for the German group. No effect was found for repetition priming ($z = 1.616$, $p = 0.212$). For the English group, ITPC was reduced for the TL compared to the control condition ($z = -3.050$, $p = .005$, $d = 0.056$), but not for the repetition compared to the control condition ($z = -1.549$, $p = 0.243$).

At parietal electrode sites, in the delta band, ITPC was higher for the repetition compared to the control condition ($z = 3.863$, $p < .001$, $d = 0.407$), but no effect was found for the TL condition ($z < 1$, $p = .747$) for the German group. For the English group, ITPC was lower for the repetition compared to the control condition ($z = -3.267$, $p = .002$, $d = 0.344$), but no effect was found for the TL condition ($z < 1$, $p = .735$). In the theta band, ITPC was higher for the repetition compared to the control condition ($z = 4.441$, $p < .001$, $d = 0.382$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$) for the German group. For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -4.227$, $p < .001$, $d = 0.364$; TL - control: $z = -3.105$, $p = .004$, $d = 0.267$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 3.227$, $p = .003$, $d = 0.241$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$) for the German group. For the English group, ITPC was higher for the TL compared to the control condition ($z = 2.539$, $p = .022$, $d = 0.189$), but no effect was found for the repetition compared to the control condition ($z = 1.096$, $p = .547$). In the beta band, ITPC was reduced for the repetition compared to the control condition ($z = -4.440$, $p < .001$, $d = 0.171$), but no effect was found for TL priming ($z = 1.063$, $p = .575$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control:

$z = 3.087$, $p = .004$, $d = 0.119$; TL - control: $z = 10.242$, $p < .001$, $d = 0.394$). In the gamma band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.074$, $p < .001$, $d = 0.086$; TL - control: $z = 7.740$, $p < .001$, $d = 0.163$) for the German group. For the English group, ITPC was lower for both primed conditions compared to the control condition (repetition - control: $z = -2.458$, $p = .028$, $d = 0.052$; TL - control: $z = -3.526$, $p < .001$, $d = 0.074$).

For the N400 time window, only a main effect of frequency band ($W(4) = 11{,}929.385$, $p < .001$, $R^2 = 5.189\cdot10^{-2}$) and a marginally significant main effect of ROI ($W(3) = 7.232$, $p = .065$, $R^2 = 3.146\cdot10^{-5}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 210.014$, $p < .001$, $R^2 = 6.231\cdot10^{-2}$) was significant. At fronto-polar electrode sites, in the delta band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.291$, $p = .044$, $d = 0.187$; TL - control: $z = 6.090$, $p < .001$, $d = 0.497$) for the German group. For the English group, ITPC was reduced for the TL compared to the control condition ($z = -2.744$, $p = .012$, $d = 0.224$), but no effect was found for the repetition condition ($z < 1$, $p = 1.000$). In the theta band, ITPC was higher for the TL compared to the control condition ($z = 3.337$, $p = .002$, $d = 0.223$), but not for the repetition compared to the control condition ($z < 1$, $p = 1.000$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 3.741$, $p < .001$, $d = 0.249$; TL - control: $z = 4.286$, $p < .001$, $d = 0.286$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 2.465$, $p = .027$, $d = 0.142$) for the German group. No effect was found for the TL condition ($z = 1.720$, $p = 0.171$). For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -2.311$, $p = .042$, $d = 0.134$; TL - control: $z = -2.812$, $p = .010$, $d = 0.162$). In the beta band, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -4.338$, $p < .001$, $d = 0.129$; TL - control: $z = -4.385$, $p < .001$, $d = 0.131$) for the German group. For the English group, ITPC was slightly higher for the repetition compared to the control condition ($z = 2.147$, $p = .064$), but no effect was found for TL priming ($z < 1$, $p = 1.000$). In the gamma band, ITPC was higher for the TL compared to the control condition ($z = 3.514$, $p < .001$, $d = 0.057$), but no effect was found for repetition priming ($z = -1.705$, $p = .176$) for the German group. For the English group, ITPC was reduced for both primed conditions compared to the control condition (repetition - control: $z = -5.923$, $p < .001$, $d = 0.097$; TL - control: $z = -6.795$, $p < .001$, $d = 0.111$).

At fronto-central electrode sites, in the delta band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.041$, $p = .083$, $d = 0.186$; TL - control: $z = 2.991$, $p = .006$, $d = 0.273$) for the German group. For the English group, ITPC for the TL condition was slightly lower compared to the control condition ($z = -2.161$, $p = .062$, $d = 0.197$), but no effect was found for repetition priming ($z = -1.298$, $p = .389$). In the theta band, no effect of condition was found for the German group ($W(2) = 2.383$, $p = .307$). For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.502$, $p < .001$, $d = 0.336$; TL - control: $z = 2.778$, $p = .011$, $d = 0.207$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 4.218$, $p < .001$, $d = 0.193$) for both groups. No effect was found for TL priming ($z < 1$, $p = 1.000$). In the beta band, ITPC was lower for both primed conditions compared to the control condition (repetition - control: $z = -9.350$, $p < .001$, $d = 0.312$; TL - control: $z = -8.463$, $p < .001$, $d = 0.282$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 2.558$, $p = .021$, $d = 0.085$; TL - control: $z = 2.758$, $p = .012$, $d = 0.092$). In the gamma band, no effect of condition was found for the German group ($W(2) = 1.478$, $p = .478$). For the English group, ITPC was lower for both primed conditions compared to the control condition (repetition - control: $z = -4.878$, $p < .001$, $d = 0.089$; TL - control: $z = -7.050$, $p < .001$, $d = 0.129$).

At centro-parietal electrode sites, in the delta band, no significant effects for condition were found. In the theta band, ITPC was marginally higher for the repetition compared to the control condition ($z = 2.054$, $p = .080$, $d = 0.153$) and marginally lower for the TL compared to the control condition ($z = -1.969$, $p = .098$, $d = 0.147$) for the German group. For the English group, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 6.263$, $p < .001$, $d = 0.467$; TL - control: $z = 4.051$, $p < .001$, $d = 0.302$). In the alpha band, ITPC was higher for the repetition compared to the control condition ($z = 4.556$, $p < .001$, $d = 0.208$) for both groups. No effect was found for TL priming ($z = 1.537$, $p = 0.249$). In the beta band, ITPC was reduced for the repetition compared to the control condition ($z = -4.573$, $p < .001$, $d = 0.152$), but not for the TL compared to the control condition ($z < 1$, $p = 1.000$) for the German group. For the English group, no effect of condition was found ($W(2) = 4.002$, $p = .135$). In the gamma band, ITPC was higher for the repetition compared to the control condition ($z = 5.887$, $p < .001$, $d = 0.108$), but no effect was found for TL priming ($z = 1.753$, $p = .159$) for the German group. For the English group, no effect of condition was found ($W(2) = 1.156$, $p = .561$).

At parietal electrode sites, in the delta band, no significant effects for condition were found. In the theta band, ITPC was higher for the repetition compared to the control condition ($z = 3.890$, $p < .001$, $d = 0.237$) for both groups. No effect of TL priming was found ($z < 1$, $p = .884$). In the alpha band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 4.120$, $p < .001$, $d = 0.307$; TL - control: $z = 2.083$, $p = .075$, $d = 0.155$) for the German group. For the English group, no effect of condition was found ($W(2) = 1.898$, $p = .387$). In the beta band, ITPC was reduced for the repetition condition compared to the control condition ($z = -8.758$, $p < .001$, $d = 0.337$), but no effect was found for the TL condition ($z = 1.442$, $p = .299$) for the German group. For the English group, no effect of condition was found ($W(2) < 1$, $p = .810$). In the gamma band, ITPC was higher for both primed conditions compared to the control condition (repetition - control: $z = 10.015$, $p < .001$, $d = 0.211$; TL - control: $z = 8.403$, $p < .001$, $d = 0.177$) for the German group. For the English group, no effect of condition was found ($W(2) = 3.675$, $p = .159$).

2.4 TF results of Experiment 3 on cross-modal transposed letter priming

TF power. The overall model showed a main effect of condition ($W(2) = 607.509$, $p < .001$, $R^2 = 1.004 \cdot 10^{-3}$), a main effect of time window ($W(1) = 3{,}631.520$, $p < .001$, $R^2 = 5.999 \cdot 10^{-3}$), a main effect of frequency band ($W(4) = 39{,}810.947$, $p < .001$, $R^2 = 6.577 \cdot 10^{-2}$) and a main effect of ROI ($W(3) = 1{,}941.759$, $p < .001$, $R^2 = 3.208 \cdot 10^{-3}$). The five-way interaction between condition, language, time window, frequency band and ROI ($W(24) = 51.202$, $p < .001$, $R^2 = 1.189 \cdot 10^{-1}$) was significant. Subsequently, I analyzed the two time windows separately. For the N250 window, main effects of condition ($W(2) = 309.575$, $p < .001$, $R^2 = 1.035 \cdot 10^{-3}$), frequency band ($W(4) = 25{,}943.259$, $p < .001$, $R^2 = 8.677 \cdot 10^{-2}$) and ROI ($W(3) = 977.830$, $p < .001$, $R^2 = 3.270 \cdot 10^{-3}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 162.795$, $p < .001$, $R^2 = 1.093 \cdot 10^{-1}$) was also significant.

At fronto-polar electrode sites, TF power in the delta band was higher for the TL compared to the control condition ($z = 2.295$, $p = .044$, $d = 0.129$), but no difference in power was found for the PsH condition compared to the TL condition ($z < 1$, $p = 1.000$). This result was irrespective of the target language. TF power in the theta band was significantly reduced for the PsH compared to the control condition ($z = -4.513$, $p < .001$, $d = 0.283$) only for the German group. But no difference was found for the TL compared to the control condition ($z < 1$, $p = .987$) and no effect was found for the English group ($W(2) = 1.459$, $p = .482$). Significantly reduced power was also found in the alpha band for both conditions (PsH - control: $z = -6.143$, $p < .001$, $d = 0.333$; TL - control: $z = -2.293$, $p = .044$, $d = 0.124$), again, only for the German group, but not effects were found for the English group (PsH - control: *z* = -1.368, *p* = .342; TL - control: *z* < 1, *p* = .732). In the beta band, TF power was reduced for the PsH condition (*z* = -3.132, *p* = .004, *d* = 0.088) and significantly enhanced for the TL condition (*z* = 5.753, *p* < .001, *d* = 0.161) for the German group. The English group showed reduced power for both primed conditions compared to the control condition (PsH - control: *z* = -4.787, *p* < .001, *d* = 0.143; TL - control: *z* = -2.248, *p* = .049, *d* = 0.067). Reduced power for both primed conditions compared to the control condition was also found in the gamma band (PsH - control: *z* = -4.253, *p* < .001, *d* = 0.065; TL - control: *z* = -4.850, *p* < .001, *d* = 0.074) for the German group. The English group showed enhanced TF power for both primed conditions compared to the control condition in this frequency band (PsH - control: *z* = 10.848, *p* < .001, *d* = 0.177; TL - control: *z* = 6.398, *p* < .001, *d* = 0.105).

At fronto-central electrode sites, TF power in the delta band was again higher for the TL compared to the control condition (*z* = 3.542, *p* < .001, *d* = 0.304) and higher for the PsH compared to the control condition (*z* = 2.315, *p* = .041, *d* = 0.199). No effect was found for the English group (*W*(2) = 1.035, *p* = .596). TF power in the theta band was significantly reduced for the PsH compared to the control condition (*z* = -5.158, *p* < .001, *d* = 0.361), but slightly enhanced for the TL condition (*z* = 2.104, *p* = .055, *d* = 0.154) for the German group. For the English group, only an enhanced TF power for the TL condition compared to the control condition (*z* = 3.750, *p* < .001, *d* = 0.280) was found in this frequency band, but no effect for the PsH condition (*z* < 1, *p* = 1.000). Significantly reduced power for the German group was also found in the alpha band for the PsH condition compared to the control condition (*z* = -6.736, *p* < .001, *d* = 0.408), but no effect was found for the TL condition (*z* < 1, *p* = .909). For the English group, enhanced power was found for the TL condition compared to the control condition (*z* = 3.484, *p* = .001, *d* = 0.225), but no effect of PsH was found (*z* < 1, *p* = .740). In the beta band, TF power was reduced for the PsH condition (*z* = -6.936, *p* < .001, *d* = 0.217), but enhanced for the TL compared to the control condition (*z* = 2.988, *p* = .006, *d* = 0.094) for the German group. For the English group, power was significantly reduced for both conditions (PsH - control: *z* = -10.091, *p* < .001, *d* = 0.336; TL - control: *z* = -6.008, *p* < .001, *d* = 0.200). In the gamma band, TF power was significantly reduced for both primed conditions compared to the control condition (PsH - control: *z* = -10.909, *p* < .001, *d* = 0.187; TL - control: *z* = -6.735, *p* < .001, *d* = 0.116) for the German group. For the English group, power in both conditions was enhanced compared to the control condition (PsH - control: *z* = 8.604, *p* < .001, *d* = 0.157; TL - control: *z* = 9.271, *p* < .001, *d* = 0.169).

At centro-parietal electrode sites, TF power in the delta band was higher for the TL compared to the control condition ($z = 3.629$, $p < .001$, $d = 0.311$) for the German group, while no effect was found for the PsH condition ($z = 1.435$, $p = .302$). For the English group, power was reduced for both primed conditions compared to the control condition (PsH - control: $z = -3.219$, $p = .003$, $d = 0.294$; TL - control: $z = -5.301$, $p < .001$, $d = 0.484$). In the theta band, TF power in the PsH condition was significantly reduced compared to the control condition ($z = -5.107$, $p < .001$, $d = 0.358$), while slightly higher power for the TL compared to the control condition ($z = 2.114$, $p = .069$, $d = 0.148$) was found for the German group. For the English group, a significant reduction in power for the PsH condition compared to the control condition ($z = -5.886$, $p < .001$, $d = 0.439$) and for the TL condition compared to the control condition ($z = -2.497$, $p = .025$, $d = 0.186$) was found. In the alpha band, TF power was reduced for both primed conditions compared to the control condition (PsH - control: $z = -7.841$, $p < .001$, $d = 0.475$; TL - control: $z = -2.282$, $p = .045$, $d = 0.138$) for the German group. For the English group, TF power was higher for the TL compared to the control condition ($z = 4.262$, $p < .001$, $d = 0.275$), but no effect was found for the PsH condition ($z < 1$, $p = 1.000$). In the beta band, TF power for both primed conditions was reduced compared to the control condition (PsH - control: $z = -9.396$, $p < .001$, $d = 0.294$; TL - control: $z = -3.699$, $p < .001$, $d = 0.116$) for the German group. For the English group, a similar pattern was observed (PsH - control: $z = -12.509$, $p < .001$, $d = 0.417$; TL - control: $z = -2.625$, $p = .017$, $d = 0.088$). In the gamma band, significantly reduced power was found for both primed conditions compared to the control condition (PsH - control: -5.687, $p < .001$, $d = 0.098$; TL - control: $z = -5.137$, $p < .001$, $d = 0.088$) for the German group. For the English group, enhanced power for the PsH compared to the control condition ($z = 4.170$, $p < .001$, $d = 0.076$) and for the TL compared to the control condition ($z = 9.880$, $p < .001$, $d = 0.180$) were found.

At parietal electrode sites, TF power in the delta band was higher for the TL condition compared to the control condition ($z = 3.041$, $p = .005$, $d = 0.301$) in the German group. No effect of PsH priming was found ($z < 1$, $p = .844$). For the English group, power in both conditions was reduced compared to the control condition (PsH - control: $z = -5.245$, $p < .001$, $d = 0.553$; TL - control: $z = -5.561$, $p < .001$, $d = 0.586$). In the theta band, TF power for the German group was significantly reduced for the PsH condition compared to the control condition ($z = -7.863$, $p < .001$, $d = 0.636$), while no effect of TL priming was found ($z < 1$, $p = 1.000$). For the English group, TF power was reduced for both conditions (PsH - control: $z = -7.823$, $p < .001$, $d = 0.673$; TL - control: $z = -3.595$, $p < .001$, $d = 0.309$). In the alpha band, power was significantly reduced for both conditions (PsH - control: $z = -8.013$, $p < .001$, $d =$

0.561; TL - control: z = -3.291, p = .002, d = 0.230) for the German group. For the English group, power was enhanced for the TL condition compared to the control condition (z = 7.144, p < .001, d = 0.533), but no effect was found for the PsH condition (z < 1, p = 1.000). In the beta band, power for the German group was significantly reduced for the PsH condition compared to the control condition (z = -7.302, p < .001, d = 0.264), but no effect of TL priming was found (z < 1, p = .638). For the English group, similar results were found (PsH - control: z = -11.595, p < .001, d = 0.446; TL - control: z < 1, p = .722). Power in the gamma band was significantly reduced for the TL condition compared to the control condition (z = -2.300, p = .043, d = 0.046), but not for the PsH compared to the control condition (z < 1, p = 1.000). For the English group, higher power was found for both primed conditions compared to the control condition (PsH - control: z = 3.421, p = .001, d = 0.072; TL - control: z = 3.281, p = .002, d = 0.069).

For the N400 time window, main effects of condition (W(2) = 378.302, p < .001, R^2 = $1.206 \cdot 10^{-3}$), frequency band (W(4) = 29,311.070, p < .001, R^2 = $9.348 \cdot 10^{-2}$) and ROI (W(3) = 1,075.270, p < .001, R^2 = $3.429 \cdot 10^{-3}$) were significant. The four-way interaction between condition, language, frequency band and ROI (W(24) = 222.979, p < .001, R^2 = $1.176 \cdot 10^{-1}$) also reached significance. At fronto-polar electrode sites, TF power was higher in the delta band for both primed conditions compared to the control condition (PsH - control: z = 3.586, p < .001, d = 0.275; TL - control: z = 4.007, p < .001, d = 0.307) for the German group. For the English group, power was only slightly enhanced for the TL condition compared to the control condition (z = 2.168, p = .060, d = 0.177), but not for the PsH condition compared to the control condition (z < 1, p = 1.000). In the theta band, TF power was higher for the PsH compared to the control condition (z = 3.471, p = .001, d = 0.217) for the German group, but no effect was found for TL priming (z = 1.625, p = .208). For the English group, power in the TL condition was higher than in the control condition (z = 5.996, p < .001, d = 0.400), but no effect for PsH priming was found (z < 1, p = 1.000). In the alpha band, power was enhanced for the PsH condition compared to the control condition (z = 4.657, p < .001, d = 0.253) for the German group, but no effect was found for TL priming (z < 1, p = 1.000). For the English group, no effect was found for either the PsH condition compared to the control condition (z = -1.763, p = .156) or for the TL compared to the control condition (z < 1, p = .833). In the beta band, power was significantly reduced for both priming conditions compared to the control condition (PsH - control: z = -4.776, p < .001, d = 0.134; TL - control: z = -5.303, p < .001, d = 0.149) for the German group. For the English group, power in both priming conditions was higher compared to the control condition (PsH - control: z = 2.026, p = .086, d = 0.060; TL - control: z = 3.980, p <

.001, *d* = 0.119). In the gamma band, power was significantly reduced for both priming conditions compared to the control condition (PsH - control: *z* = -16.506, *p* < .001, *d* = 0.156; TL - control: *z* = -6.888, *p* < .001, *d* = 0.173) for the German group. For the English group, power in both primed conditions was significantly enhanced compared to the control condition (PsH - control: *z* = 29.724, *p* < .001, *d* = 0.080; TL - control: *z* = 15.141, *p* < .001, *d* = 0.157).

At fronto-central electrode sites, in the delta band power was significantly higher for both primed conditions compared to the control condition (PsH - control: *z* = 5.318, *p* < .001, *d* = 0.456; TL - control: *z* = 6.217, *p* < .001, *d* = 0.533) for the German group. For the English group, only power in the TL condition was enhanced (*z* = 2.742, *p* = .012, *d* = 0.396), but no effect for PsH priming was found (*z* < 1, *p* = 1.000). In the theta band, power for the German group was significantly higher in the TL condition compared to the control condition (*z* = 4.312, *p* < .001, *d* = 0.302), but no effect of PsH priming was found (*z* = 1.683, *p* = .185). For the English group, the same pattern of results was found (PsH - control: *z* < 1, *p* = .667; TL - control: *z* = 7.160, *p* < .001, *d* = 0.534). In the alpha band, power for the German group was significantly higher for the TL condition compared to the control condition (*z* = 4.291, *p* < .001, *d* = 0.260), while no effect was found for the PsH condition (*z* < 1, *p* = 1.000). For the English group, power in the PsH condition was significantly reduced compared to the control condition (*z* = -3.351, *p* = .002, *d* = 0.216), while no effect was found for the TL condition compared to the control condition (*z* = 1.846, *p* = .130). In the beta band, power in both primed conditions was reduced compared to the control condition (PsH - control: *z* = -5.988, *p* < .001, *d* = 0.188; TL - control: *z* = -2.576, *p* = .020, *d* = 0.081) for the German group. For the English group, power was higher in the TL condition compared to the control condition (*z* = 3.700, *p* < .001, *d* = 0.123), but no effect was found for the PsH condition (*z* < 1, *p* = .894). Power in the gamma band was significantly reduced for both primed conditions compared to the control condition (PsH - control: *z* = -22.040, *p* < .001, *d* = 0.378; TL - control: *z* = -5.949, *p* < .001, *d* = 0.102) for the German group. For the English group, power was higher in both primed conditions compared to the control condition (PsH - control: *z* = 18.372, *p* < .001, *d* = 0.335; TL - control: *z* = 15.575, *p* < .001, *d* = 0.284).

At centro-parietal electrode sites, power for the German group in the delta band was higher for the PsH condition compared to the control condition (*z* = 4.945, *p* < .001, *d* = 0.424) and for the TL condition compared to the control condition (*z* = 7.209, *p* < .001, *d* = 0.618). For the English group, power in the PsH condition was reduced compared to the control condition (*z* = -2.435, *p* = .030, *d* = 0.222), but no effect was found for the TL condition (*z* = -1.369, *p* = .342). In the theta band, power was higher in the TL condition compared to the control condition (*z* = 5.784, *p* < .001, *d* = 0.405) for the German group, while no effect for PsH priming was found (*z* < 1, *p* = 1.000). For the English group, power was lower in the PsH condition compared to the control condition (*z* = -2.691, *p* = .014, *d* = 0.201), but higher in the TL compared to the control condition (*z* = 3.191, *p* = .003, *d* = 0.238). In the alpha band, power was significantly reduced for the PsH compared to the control condition (*z* = -4.438, *p* < .001, *d* = 0.197) and higher for the TL condition compared to the control condition (*z* = 6.321, *p* < .001, *d* = 0.280) for both groups. In the beta band, TL power was reduced in the TL condition compared to the control condition (*z* = -2.318, *p* = .041, *d* = 0.073) for the German group. No effect of PsH priming was found (*z* < 1, *p* = .689). For the English group, power in the PsH condition was significantly reduced compared to the control condition (*z* = -10.957, *p* < .001, *d* = 0.365), but no effect of TL priming was found (*z* < 1, *p* = .664). In the gamma band, power was reduced for the PsH condition compared to the control condition (*z* = -13.542, *p* < .001, *d* = 0.232), but no effect was found for the TL compared to the control condition (*z* < 1, *p* = .856) for the German group. For the English group, power in both conditions was higher than in the control condition (PsH - control: *z* = 12.483, *p* < .001, *d* = 0.228; TL - control: *z* = 9.353, *p* < .001, *d* = 0.171).

At parietal electrode sites, in the delta band, power was higher in both primed conditions compared to the control condition (PsH - control: *z* = 2.813, *p* = .010, *d* = 0.279; TL - control: *z* = 6.905, *p* < .001, *d* = 0.684) for the German group. For the English group, power in both primed conditions was reduced compared to the control condition (PsH - control: *z* = -4.919, *p* < .001, *d* = 0.519; TL - control: *z* = -3.418, *p* = .001, *d* = 0.360). In the theta band, power was reduced for the PsH condition compared to the control condition (*z* = -2.473, *p* = .027, *d* = 0.200), but higher in the TL condition compared to the control condition (*z* = 4.127, *p* < .001, *d* = 0.334) for the German group. For the English group, power in the PsH condition was significantly reduced compared to the control condition (*z* = -5.240, *p* < .001, *d* = 0.451), but no effect of TL priming was found (*z* < 1, *p* = 1.000). In the alpha band, power was significantly reduced for the PsH condition compared to the control condition (*z* = -4.731, *p* < .001, *d* = 0.331) for the German group. For the TL condition, no effect was found (*z* < 1, *p* = .914). For the English group, power in the TL condition was higher compared to the control condition (*z* = 6.788, *p* < .001, *d* = 0.506), but no effect was found for the PsH condition compared to the control condition (*z* = -1.569, *p* = .233). In the beta band, no effect of condition was found for the German group (*W*(2) = 3.775, *p* = .151). For the English group, power in the PsH condition was reduced compared to the control condition (*z* = -10.074, *p* < .001, *d* = 0.388), but no effect was found for the TL compared to the control condition (*z* < 1, *p* = 1.000). In the gamma band, power was enhanced in the TL condition compared to the control condition ($z = 9.619$, $p < .001$, $d = 0.191$), but no effect was found for the PsH condition compared to the control condition ($z < 1$, $p = 1.000$) for the German group. For the English group, no effect of condition was found ($W(2) = 4.303$, $p = .116$).

ITPC. The overall model showed a main effect of condition ($W(2) = 133.860$, $p < .001$, $R^2 = 1.986 \cdot 10^{-4}$), a main effect of time window ($W(1) = 8{,}767.000$, $p < .001$, $R^2 = 1.300 \cdot 10^{-2}$), a main effect of frequency band ($W(4) = 135{,}150.000$, $p < .001$, $R^2 = 2.005 \cdot 10^{-1}$) and of ROI ($W(3) = 225.100$, $p < .001$, $R^2 = 3.340 \cdot 10^{-4}$). The five-way interaction between condition, language, time window, frequency band and ROI ($W(24) = 195.580$, $p < .001$, $R^2 = 3.149 \cdot 10^{-1}$) was also significant. For the N250 time window, a main effect of condition ($W(2) = 77.998$, p < .001, $R^2 = 2.053 \cdot 10^{-4}$), of frequency band ($W(4) = 143{,}180.000$, $p < .001$, $R^2 = 3.769 \cdot 10^{-1}$) and of ROI ($W(3) = 241.600$, $p < .001$, $R^2 = 6.360 \cdot 10^{-4}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 178.710$, $p < .001$, $R^2 = 3.876 \cdot 10^{-1}$) also reached significance.

At fronto-polar electrode sites, no effect of condition was found in the delta band for the German group ($W(2) = 1.191$, $p = .551$). For the English group, ITPC in the delta band was slightly higher for the PsH compared to the control condition ($z = 2.105$, $p = .071$, $d = 0.172$), but no effect was found for the TL compared to the control condition ($z < 1$, $p = .885$). In the theta band, no effect was found for either the PsH condition compared to the control condition ($z = -1.845$, $p = .130$) or for the TL condition ($z < 1$, $p = .722$) for the German group. For the English group, ITPC was higher in the PsH condition compared to the control condition ($z = 4.091$, $p < .001$, $d = 0.273$), but no effect was found for the TL condition ($z = -1.007$, $p = .628$). In the alpha band, ITPC was reduced for the TL compared to the control condition ($z = -4.563$, $p < .001$, $d = 0.248$) for the German group, but no effect was found for the PsH condition ($z = -1.047$, $p = .591$). For the English group, ITPC was higher for the PsH compared to the control condition ($z = 2.344$, $p = .038$, $d = 0.135$), but no effect was found for the TL condition ($z = -1.163$, $p = .489$). In the beta band, ITPC was reduced for the PsH condition compared to the control condition ($z = -8.182$, $p < .001$, $d = 0.229$), but no effect was found for the TL condition ($z < 1$, $p = .942$) for the German group. For the English group, ITPC was reduced for the TL condition compared to the control condition ($z = -5.140$, $p < .001$, $d = 0.153$), but no effect was found for the PsH condition ($z = -1.908$, $p = .113$). In the gamma band, ITPC was higher in both primed conditions compared to the control condition (PsH - control: $z = 6.296$, $p < .001$, $d = 0.097$; TL - control: $z = 10.601$, $p < .001$, $d = 0.163$) for the German group. For the English group, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -9.759$, $p < .001$, $d = 0.159$; TL - control: $z = -6.922$, $p < .001$, $d = 0.113$).

At fronto-central electrode sites, no significant effects were found in the delta band. In the theta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -4.795$, $p < .001$, $d = 0.336$; TL - control: $z = -3.808$, $p < .001$, $d = 0.267$) for the German group. For the English group, ITPC was higher for the PsH condition compared to the control condition ($z = 2.710$, $p = .014$, $d = 0.202$), but no effect was found for the TL condition ($z < 1$, $p = 1.000$). In the alpha band, ITPC for the TL condition was significantly reduced compared to the control condition ($z = -5.794$, $p < .001$, $d = 0.351$) for the German group. No effect was found for the PsH condition compared to the control condition ($z < 1$, $p = 1.000$). For the English group, no effect of condition ($W(2) = 2.339$, $p = .311$) was found. In the beta band, ITPC was significantly higher for the TL condition compared to the control condition ($z = 4.143$, $p < .001$, $d = 0.130$) for the German group, but no effect was found for the PsH condition ($z < 1$, $p = 1.000$). For the English group, ITPC was reduced for the TL compared to the control condition ($z = -2.503$, $p = .025$, $d = 0.083$), but no effect was found for the PsH condition ($z < 1$, $p = .814$). In the gamma band, ITPC was higher for the PsH condition compared to the control condition ($z = 4.104$, $p < .001$, $d = 0.070$) and lower for the TL compared to the control condition ($z = -2.823$, $p = .010$, $d = 0.048$) for the German group. For the English group, ITPC in both primed conditions was reduced compared to the control condition (PsH - control: $z = -7.869$, $p < .001$, $d = 0.144$; TL - control: $z = -9.592$, $p < .001$, $d = 0.175$).

At centro-parietal electrode sites, no effects were found in the delta band. In the theta band, both primed conditions showed reduced ITPC compared to the control condition (PsH - control: $z = -6.374$, $p < .001$, $d = 0.446$; TL - control: $z = -5.574$, $p < .001$, $d = 0.390$) for the German group. For the English group, no effect of condition ($W(2) = 3.109$, $p = .211$) was found. In the alpha band, ITPC was reduced for the PsH condition compared to the control condition ($z = -6.212$, $p < .001$, $d = 0.377$) and for the TL condition ($z = -9.147$, $p < .001$, $d = 0.555$) for the German group, while no effect was found for the English group ($W(2) < 1$, $p = .650$). In the beta band, ITPC was lower for the PsH compared to the control condition ($z = -3.075$, $p = .004$, $d = .070$) and higher for the TL condition compared to the control condition ($z = 3.140$, $p = 0.003$, $d = 0.072$) for both groups. In the gamma band, ITPC for the German group was higher in the PsH compared to the control condition ($z = 2.677$, $p = .015$, $d = 0.046$), but no effect of TL priming was found ($z < 1$, $p = .662$). For the English group, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -9.962$, $p < .001$, $d = 0.182$; TL - control: $z = -9.534$, $p < .001$, $d = 0.174$).

At parietal electrode sites, in the delta band, no significant effects were found. In the theta band, ITPC for both primed conditions was reduced compared to the control condition (PsH - control: $z = -8.389$, $p < .001$, $d = 0.678$; TL - control: $z = -5.993$, $p < .001$, $d = 0.485$) for the German group. For the English group, ITPC was higher for the TL compared to the control condition ($z = 2.454$, $p = .028$, $d = 0.211$), but no effect was found for the PsH condition ($z = 1.663$, $p = .193$). In the alpha band, ITPC for both primed conditions was reduced compared to the control condition (PsH - control: $z = -8.364$, $p < .001$, $d = 0.586$; TL - control: $z = -9.248$, $p < .001$, $d = 0.648$) for the German group. For the English group, ITPC was reduced for the TL compared to the control condition ($z = -3.449$, $p < .001$, $d = 0.257$), but no effect was found for the PsH condition ($z < 1$, $p = .928$). In the beta band, ITPC was reduced for the PsH compared to the control condition ($z = -2.829$, $p = .009$, $d = 0.075$) and enhanced for the TL compared to the control condition ($z = 5.123$, $p < .001$, $d = 0.135$) for both groups. In the gamma band, ITPC for the German group was higher in the PsH compared to the control condition ($z = 7.823$, $p < .001$, $d = 0.155$), but no effect was found for the TL condition ($z = 1.727$, $p = .168$). For the English group, ITPC was lower for the TL compared to the control condition ($z = -6.314$, $p < .001$, $d = 0.133$), but no effect was found for the PsH compared to the control condition ($z < 1$, $p = 1.000$).

For the N400 time window, a main effect of condition ($W(2) = 58.817$, $p < .001$, $R^2 = 2.374 \cdot 10^{-4}$), a main effect of frequency band ($W(4) = 13{,}279.179$, $p < .001$, $R^2 = 5.360 \cdot 10^{-2}$) and a main effect of ROI ($W(3) = 62.443$, $p < .001$, $R^2 = 2.520 \cdot 10^{-4}$) were found. The four-way interaction between condition, language, frequency band and ROI ($W(24) = 230.618$, $p < .001$, $R^2 = 6.548 \cdot 10^{-2}$) was also significant. At fronto-polar electrode sites, in the delta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -5.354$, $p < .001$, $d = 0.411$; TL - control: $z = -4.992$, $p < .001$, $d = 0.383$) for the German group. For the English group, no effect of condition was found ($W(2) = 2.972$, $p = .226$). In the theta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -4.354$, $p < .001$, $d = 0.273$; TL - control: $z = -9.482$, $p < .001$, $d = 0.594$) for the German group. For the English group, a similar pattern was found (PsH - control: $z = -2.812$, $p < .001$, $d = 0187$; TL - control: $z = -4.751$, $p < .001$, $d = 0.317$). In the alpha band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: $z = -8.358$, $p < .001$, $d = 0.453$; TL - control: $z = -15.047$, $p < .001$, $d = 0.816$) for the German group. For the English group, ITPC was higher in the TL condition compared to the control condition ($z =$

3.340, *p* = .002, *d* = 0.193), but no effect was found for the PsH condition (*z* < 1, *p* = 1.000). In the beta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -9.067, *p* < .001, *d* = 0.254; TL - control: *z* = -7.696, *p* < .001, *d* = 0.216) for the German group. For the English group, ITPC was higher for the TL compared to the control condition (*z* = 2.738, *p* = .012, *d* = 0.082) and lower for the PsH compared to the control condition (*z* = -4.611, *p* < .001). In the gamma band, ITPC was higher for both primed conditions compared to the control condition (PsH - control: *z* = 3.375, *p* = .002, *d* = 0.308; TL - control: *z* = 5.378, *p* < .001, *d* = 0.261) for the German group. For the English group, no effect of condition was found (*W*(2) < 1, *p* = .953).

At fronto-central electrode sites, in the delta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -5.366, *p* < .001, *d* = 0.460; TL - control: *z* = -4.444, *p* < .001, *d* = 0.381) for the German group. No effects were found for the English group (*W*(2) = 3.217, *p* = .200). In the theta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -2.526, *p* = .023, *d* = 0.177; TL - control: *z* = -8.033, *p* < .001, *d* = 0.562) for the German group. A similar pattern was found for the English group (PsH - control: *z* = -2.871, *p* = .008, *d* = 0.214; TL - control: *z* = -2.414, *p* = .032, *d* = 0.180). In the alpha band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -3.182, *p* = .003, *d* = 0.193; TL - control: *z* = -9.576, *p* < .001, *d* = 0.581) for the German group. For the English group, ITPC in the TL condition was higher than in the control condition (*z* = 5.023, *p* < .001, *d* = 0.324), but no effect was found for the PsH condition (*z* < 1, *p* = .657). In the beta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -3.646, *p* < .001, *d* = 0.114; TL - control: *z* = -3.853, *p* < .001, *d* = 0.121) for the German group. For the English group, ITPC was higher for the TL condition compared to the control condition (*z* = 5.378, *p* < .001, *d* = 0.179), but no effect was found for the PsH condition (*z* < 1, *p* = .640). In the gamma band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -4.170, *p* < .001, *d* = 0.072; TL - control: *z* = -3.665, *p* < .001, *d* = 0.063) for the German group. For the English group, ITPC in the PsH condition was significantly lower than in the control condition (*z* = -2.300, *p* = .043, *d* = 0.042), but no effect was found for the TL condition (*z* < 1, *p* = 1.000).

At centro-parietal electrode sites, in the delta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: *z* = -4.949, *p* < .001, *d* = 0.424; TL - control: *z* = -3.781, *p* < .001, *d* = 0.324) for the German group. No effects were found for the English group (*W*(2) = 1.284, *p* = .523). In the theta band, ITPC was lower for the TL compared to the control condition (z = -2.573, p = .020, d = 0.180) for the German group, but no effects were found for the PsH condition (z < 1, p = 1.000). For the English group, no effects of condition were found (W(2) = 1.777, p = .250). In the alpha band, ITPC was higher for both primed conditions compared to the control condition (PsH - control: z = 5.117, p < .001, d = 0.310; TL - control: z = -2.136, p = .065, d = 0.130) for the German group. For the English group, ITPC was higher for the TL compared to the control condition (z = 2.207, p = .055, d = 0.142), but no effect was found for the PsH condition (z < 1, p = .840). In the beta band, ITPC was higher for the PsH condition compared to the control condition (z = 3.424, p = .001, d = 0.107) and marginally higher for the TL compared to the control condition (z = 2.001, p = .091, d = 0.063) for the German group. For the English group, ITPC was higher in both primed conditions compared to the control condition (PsH - control: z = 5.961, p < .001, d = 0.199; TL - control: z = 10.004, p < .001, d = 0.333). In the gamma band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: z = -7.462, p < .001, d = 0.128; TL - control: z = -2.252, p = .049, d = 0.039) for the German group. For the English group, ITPC was higher for the PsH condition compared to the control condition (z = 3.664, p < .001, d = 0.067), but not for the TL condition compared to the control condition (z < 1, p = .756).

At parietal electrode sites, in the delta band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: z = -2.386, p = .036, d = 0.235; TL - control: z = -2.006, p = .090, d = 0.199) for the German group. For the English group, no effect of condition was found (W(2) = 3.893, p = .143). In the theta band, ITPC was lower for both primed conditions compared to the control condition (PsH - control: z = -3.118, p = .004, d = 0.252; TL - control: z = -4.175, p < .001, d = 0.338) for the German group. No effect was found for the English group (W(2) = 3.190, p = .203). In the alpha band, ITPC was reduced for both primed conditions compared to the control condition (PsH - control: z = -3.189, p = .003, d = 0.163; TL - control: z = -3.257, p = .002, d = 0.167) for both groups. In the beta band, ITPC was reduced for the TL condition compared to the control condition (z = -2.794, p = .010, d = 0.101), but not for the PsH condition compared to the control condition (z < 1, p = .815) for the German group. For the English group, ITPC was higher in both primed conditions compared to the control condition (PsH - control: z = 6.270, p < .001, d = 0.241; TL - control: z = 8.262, p < .001, d = 0.318). In the gamma band, ITPC was reduced for the PsH condition compared to the control condition (z = -3.973, p < .001, d = 0.079), but no effect was found for the TL compared to the control condition (z < 1, p = .696) for the German group. For the English group, ITPC was higher for the PsH compared to the control condition ($z = 11.474$, $p < .001$, $d = 0.242$), but reduced for the TL condition compared to the control condition ($z = -3.531$, $p < .001$, $d = 0.074$).

Curriculum Vitae

Education

Oct 2021 – Jun 2024	**M.Sc. Psychology** Johann Wolfgang von Goethe-University Frankfurt (Main), Germany Major: Cognitive Neuroscience, Minor: Clinical Psychology
Apr 2018 – Mar 2024	**PhD in Neurolinguistics** Philipps-University Marburg, Germany
Apr 2014 – Mar 2021	**B.Sc. Psychology (part-time)** University of Hagen, Germany
Apr 2016 – Mar 2018	**M.A. Linguistics: Cognition and Communication** Philipps-University Marburg, Germany Major: Psycho- and Neurolinguistics
Oct 2011 – Sep 2015	**B.A. European Studies** University of Passau, Germany Major: Linguistics

Professional appointments

Feb 2024 – Present	**Lead Behavioral Therapist** Hand in Hand Ltd. Rabat, Malta
Apr 2018 – Sep 2023	**Research and Teaching Assistant** Neurolinguistics Group, Philipps-University Marburg Germany
May 2016 – Mar 2018	**Student Assistant** Clinical Linguistics Group, Philipps-University Marburg Germany

Publications, scientific talks, and posters

Türk, S., & Domahs, U. (in revision). Unimodal and cross-modal transposed letter priming effects in late German-English bilinguals are evidence for the bimodal processing of words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Türk, S., & Domahs, U. (2022). Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language. *Brain & Language, 235*, 105186.

Türk, S., & Domahs, U. (2023). Cross-modal transposed letter priming effects are evidence for the bimodal processing of words. Poster presented at the annual meeting of the Society for the Neurobiology of Language, Marseille, France.

Türk, S., Stein, F., Eiche, L., Buck, M., Kircher, T., & Domahs, U. (2023). Semantic Priming in Major Depressive Disorder: An Electrophysiological Investigation. Poster presented at the CMBB conference day, Giessen, Germany.

Türk, S., & Domahs, U. (2022). Orthographic influences on spoken word recognition in bilinguals are dependent on the orthographic depth of the target language not the native language. Talk held at the International Conference on the Mental Lexicon, Niagara-on-the-lake, Canada.

Türk S., & Domahs, U. (2022). Orthographic and phonological influence on spoken word recognition in German-English bilinguals - Evidence from transposed letter, repetition and pseudohomophone priming. Poster presented at the International Conference on the Mental Lexicon, Niagara-on-the-lake, Canada.

Türk, S., Gerards, J., Scharinger, M., & Domahs, U. (2022). MMN patterns in the processing of German mid-high vowels in native and non-native speakers. Talk held at the Conference on Laboratory Phonology, online.

Türk, S., & Domahs, U. (2020). Bimodal processing of spoken words: On orthographic influences on spoken word recognition in bilinguals. Talk held at the Words in the World International Conference (WoW), online.

Türk, S., Gerards, J., Scharinger, M., & Domahs, U. (2020). Processing of native and non-native vowel contrasts in German and Spanish speakers: Asymmetric responses to German mid-high vowels. Poster presented at the PhonolEEGy, Nice, France/online.

Türk, S., & Domahs, U. (2019). Orthographic influences on spoken word recognition in a shallow orthography in native speakers and second language learners. Talk held at the International Workshop on Reading and Developmental Dyslexia (iWORDD), Donostia-San Sebastián, Spain.

Türk, S., & Domahs, U. (2019). Orthographic influences on spoken word recognition in a shallow orthography in native speakers and second language learners. Poster presented at the Conference on a multimodal view of language and the interactions of different language modalities (LingCologne), Cologne, Germany.