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Phonological awareness of bilinguals in visual word recognition

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The present study, in which the phonological awareness of bilinguals and the temporal characteristics of written word recognition are studied with mixed language lexical decision tests, is a part of a larger-scale research. The study aims to collect information about the temporal characteristics of word recognition at the orthographic, phonological, and semantic levels of processing. The current research explores the ERP-patterns during the recognition of Hungarian (L1) and English (L2) words, pseudo-words, and non-words. Twenty-three Hungarian–English bilingual participants were tested in an EEG laboratory. All of them have C1 level English proficiency and use English at work and in their everyday lives on a daily basis. In the lexical decision task, the N170 (left temporal electrodes) and N400 (central electrodes) components were more pronounced in word trials than in non-word trials. This activity probably reflects the integrational and meaning-matching processes during word recognition. In the language decision task on pseudo-words, the Hungarian-like strings elicited a late (300-600) negative component at the left frontal electrode sites, missing from the ERP of the English-like strings. Note that the task is different in the two experiments, which probably influences the stimulus processing and the elicited ERP waveforms as well. In the language decision task, phonological awareness has a crucial role, attributing to the observed differences.

Keywords: *EEG, ERP, bilingual lexical decision, visual word recognition, phonological awareness*

1. INTRODUCTION

What happens to our brain when we see or hear a word? How do we process written information from the onset of the stimulus to the full comprehension of an isolated word? The present paper gives an overview of written word recognition, which is certainly an important component of language comprehension. Words are elementary units of language, and they are present in both spoken and written language. Perception of the printed word is a fundamental skill in such basic everyday activities as reading. Although the identification of printed words is well-researched in monolingual contexts, bilingual written language processing is still an under-researched area especially with Hungarian as a component of bilingualism. At the same time, research on bilingual written word processing can provide crucial information not only for researchers but also for teachers who deal with bi- or multilingual children and facilitate their literacy development. The present study focuses on the recognition of isolated words coming from two languages: English and Hungarian.

1.1. Bilingual visual language processing

In bilingual visual language processing, the focus of research is on the brain activations that occur when two languages are being processed at a time, with the participant being in a bilingual mode. Word recognition is the moment when there is a match between the printed word and one of the orthographic forms stored in the mental lexicon, i.e. lexical access is successful. The mental lexicon includes all the orthographic, phonological, morphological, and syntactic information, and most importantly, the meaning of each word. Word recognition includes the whole mental activity from the perception of the word until the knowledge with its lexical representation is available (De Groot, 2011).

One of the most efficient methods for demonstrating the time course of the complex processes of the brain, and for measuring bilingual visual word recognition is EEG correlates and ERP components of visual lexical decision tasks. Phonological awareness is assumed to have a great role in this process. The two frequently researched types of lexical decision tasks are the ones that include pseudo-words and non-words and study their recognition processes. Non-words are nonsense letter strings. Pseudo-words are meaningless letter strings that meet the requirements of the orthography and phonology of the test language. Testing word recognition with non-words provides an insight into the word superiority effect, while using pseudo-words in the tests, sheds light on the phonological awareness of the participants.

1.2. Processing languages with different writing systems

The psycholinguistic and neurolinguistic research into bilingualism has been focusing on (i) how languages are stored in the brain and how they are processed; (ii) whether there are two separate lexicons or there is one common lexicon that contains all the information; (iii) whether the conceptual representation is common or separate; and (iv) how the lexicons are connected to each other and to the conceptual representation. Early studies claim words are stored and retrieved in a network of associations (Nattinger, 1988), but recent brain mapping evidence shows that concepts are distributed all across the brain, in both hemispheres (Kiefer & Pulvermüller, 2012; Zhang et al., 2020). The question is how the mind controls two linguistic systems: whether bilinguals store linguistic information in a unified system and have identical access to both languages, or the information storage is linked to separate languages, i.e. two separate mental lexicons (Appel & Muysken, 1987; De Groot, 2011). One of the most prominent questions concerning the bilingual mental lexicon is whether lexical access is selective or non-selective. There is a general agreement among researchers that bilingual lexical access is characterized by non-selectivity (De Groot et al., 2000; Dijkstra & Van Heuven, 1998, 2002). Non-selectivity is true for orthographic (De Groot & Nas, 1991) and phonological codes (Duyck, 2005; Jared & Kroll, 2001). There is also a widely accepted consensus about continuous co-activation at all linguistic levels, including phonology, syntax, and semantics (Dijkstra, 2005; Dijkstra & Van Heuven, 2002; Miwa & Baayen, 2021; Peeters et al., 2018; Schmid, 2010).

Behavioral studies (Weber Fox & Neville, 1996) examining L1 and L2 support the idea of linguistic skills (phonological, semantic, grammatical, and syntactic) having an influence on bilingual visual word recognition. In human-spoken languages, phonology is strongly involved in reading from the very beginning (Perfetti et al., 1992). Phonological processing begins right away when the reader interacts with a letter string (Halderman et al., 2012).

Skilled readers have access to multi-layer phonological representations during word recognition, and they also identify information about consonants and vowels, syllables, sub-phonemic information (voicing), segmental and suprasegmental features easily and quite quickly (Halderman et al., 2012). Furthermore, eye movement studies also prove that phonological awareness strongly contributes to reading skills. Rayner et al. (1995) appraise that phonological information is processed at as early as 170 ms, and Event-Related Potentials (ERP) studies also confirm that lexical processing begins in the first 200 ms (Pulvermüller et al., 1995).

1.3. Visual word recognition models

Bilingual visual word recognition studies the neurocognition of two languages. Word recognition models illustrate how bilinguals select between their languages, and how words and their linguistic information are stored in the mental lexicon.

1.3.1. The Multiple Read-Out Model (MROM)

Grainger and Jacobs (1996) designed a connectionist model, the Multiple Read-Out Model, which explains the characteristic features of word recognition in lexical decision tests. According to MROM, the lexical decision depends on three criteria. The first criterion is the activation level of words, the second is the global lexical activation, and the third is the time limit. The first two criteria are based on interlexical information that helps positive decisions (real words), and the third criterion is specified by the time starting from the onset of the stimulus, which increases the probability of negative decisions (non-words). According to the authors, MROM is capable of predicting the reaction time based on the features of pseudo-words (orthographic neighbors, frequency). Grainger and Jacobs' (1996) multiple read-out model provides a theoretical summary based on the previous results of lexical decision tasks and it describes the recognition of not just words but pseudo-words, as well. This model says that lexical decision is affected by different factors, which are the activation of individual lexical units, and the activation of global or summed lexical units. If a lexical word node is connected to any of the word nodes in the mental lexicon, the stimulus is identified as an existing word, which results in a 'word' decision. However, according to the authors, lexical decisions can also be done without lexical access to a certain word representation. This is the so-called fast-guess mechanism that relies on familiarity. The second factor is based on a summed, global lexical activation over all word nodes. When this summed or global unit is reached, a 'word' response is given, and a 'non-word' response is given when the temporal criterion is reached before either the local or the global criteria is reached.

1.3.2. The Bilingual Interactive Activation (BIA) model

Based on the Interactive Activation (IA) model for monolingual visual word recognition (McClelland & Rumelhart, 1981), Dijkstra and Van Heuven (1998) developed the Bilingual Interactive Activation (BIA) model. The BIA model represents visual letter features, letters, orthographic word forms, and language information. According to this model, visual letter features and letters are stored in a common system, whereas words are stored in different linguistic subsystems. During the reading process, feature nodes activate relevant letters, letter nodes activate words in the relevant language, and words from both languages might interact in the bilingual word recognition processes. The word activates the target language, and the non-target language gets deactivated (Grant et. al., 2019).

1.3.3 The semantic, orthographic, and phonological interactive activation (SOPHIA) model

Since the BIA model does not include semantics, Van Heuven and Dijkstra (2001) developed the Semantic, Orthographic and Phonological Interactive Activation (SOPHIA) model. This model describes the levels of visual and auditory word recognition. The first level of the model is sublexical orthography and sublexical phonology, which are in constant interaction with each other. The second level represents orthographic words and phonological words, which also interact with each other and with the first level. The sublexical features (orthography and phonology) activate the word of the appropriate language and inhibit the activation of the non-target language. The target language gets activated, and the semantic level is also significant at this point since it is responsible for deciding whether the word has a meaning or not.

1.3.4. The Bilingual Interactive Activation+ (BIA+) model

The original BIA model was extended by semantic and phonological representations, and a non-linguistic task/decision subsystem was added to the word identification subsystem. In the word identification subsystem (similarly to the SOPHIA model), the sublexical orthography and the sublexical phonology are in continuous interaction with each other, and the lexical orthography and lexical phonology are in connection, as well. In this subsystem, the input is processed on the level of sublexical orthography and phonology and then on the level of lexical orthography and phonology. When the target language is chosen, the semantics of the word is checked. This is an interactive model, since the levels are connected to each other and the information can be sent back to the previous subsystem to confirm. When the appropriate language is chosen, the semantics of the word is checked. The task/decision subsystem receives the input from the identification subsystem, where the correct language is identified and gets activated (Dijkstra & Van Heuven, 2002).

1.4. Pseudo-words: Phonotactic restrictions on English and Hungarian syllables

Hungarian has a shallow writing system and is built on a consistent mapping of graphemes to phonemes; English has a deep one and there is no grapheme-phoneme correspondence rule in it. Unlike in Hungarian, in English, the same letter (or sequence of letters) may be pronounced in different ways depending on their position within a word (Crystal, 2020), and also several graphemes can represent only one phoneme.

Both languages have strict restrictions on what graphemes can appear in what order in what position (phonotactic rules). A letter string can be a potential word (pseudo-word) as it contains some combination, which is systematically acceptable by either language system.

Singleton (1999) claims that the phonological and morphological forms of the word determine which lexicon gets activated first and where the word recognition takes place. He argues that when bilinguals, who speak two typologically unrelated languages, read a word, a language-specific letter string immediately activates the appropriate language, since the other language lacks that combination of letters. The phonotactic rules and the restrictions on syllable structures in English and Hungarian are very different.

1.4.1. Neurological aspects of pseudo-word recognition

The occipital P100 (positive deflection peaking around 100 ms) is the first component responding to visual stimuli. Although this is not specific to the processing of words, this is when the initial steps are made. The left occipito-temporal N170 (negative deflection peaking around 170 ms) is an ERP component that reflects the neural processing of wordforms. This integrative process is stronger for stimuli that code sensible information, i.e., real words over non-words. The N400 (negative deflection peaking around 400 ms) is understood to reflect the meaning of stimuli. This is when lexico-semantic processing takes place.

In language decision tasks, pseudo-words evoke larger amplitude N400s than words (Braun et al., 2006). According to Braun et al. (2006) the amount of neural activity depends on two important factors. On one hand, it depends on the difficulty of the visual word processing itself, in the sense that there is more neural activity and greater N400 amplitude when the processing is more difficult due to the low frequency of the word or the low predictability of the word in a certain context. On the other hand, neural activity is affected by the global amount of information, in the sense that there is more neural activity and greater N400 amplitude when more information is being activated, for example in the case of concrete words that activate rich semantic representations. In the case of pseudo-words N400 is larger, since the mental lexicon needs greater effort to search for their lexical representations.

Pseudo-words cause greater activations in certain brain regions than real words (Carreiras et al., 2013; De Groot, 2011). This greater brain activity clarifies that unknown stimuli that are incapable of accessing word associations might activate the neuronal network more than words that the individual is already familiar with.

In fMRI studies of brain mechanisms for reading words and pseudo-words (c.f. Hagoort et al., 1999; Simos et al., 2002), researchers found that reading real words resulted in activations in the left posterior middle temporal gyrus and in the mesial temporal lobe areas, while reading pseudo-words ends up in higher activations in the posterior superior temporal gyrus, and in the interior parietal and basal temporal areas. They also claim that pseudo-words are associated with word-specific mental representations. In the case of pseudo-words and words that have rare equivocal grapheme-phoneme correspondence, the lexical representation generates the retrieval of the word. Based on this, the recognition of pseudo-words requires a high level of phonological awareness. On the other hand, for an experienced reader, reading a frequent real word and recognizing it is rather an automatized process. The importance of word frequency is also emphasized in another study by Simos et al. (2000), in which they gained evidence for activations in different brain areas depending on word frequency.

Hagoort et al. (1999) found bilateral activation in medial and lateral extrastriate areas and in the left lower precentral gyrus during silent reading of both words and pseudo-words, which proves that the auditory form of the word gets activated in silent reading, and emphasizes the role of phonological processing.

A very efficient method for testing bilingual word recognition theory is the study of the electroencephalogram (EEG) and event-related potential (ERP) components. EEG is a non-invasive technique, which measures brain electrical activity with high temporal precision but limited localization. The electrical signals reflect - among others - the processing of environmental stimuli. By precisely aligning and averaging stimulus-locked segments of the EEG recording, we can remove the incidental noise and observe an ERP, the potential changes evoked by the stimulus. Immediately after the onset of the stimulus, the visual cortex gets activated. In the waveform, positive and negative deflections are the result of overlapping ERP components, indicative of the underlying neural processes. Since ERP components can overlap, amplitude changes are difficult to interpret.

1.5. Orthographic neighborhood density

The effect of orthographic neighborhood density is among the most significant findings in visual word recognition. The terms 'orthographic neighbors' and 'orthographic neighborhood' were first used by Landauer and Streeter (1973). According to Landauer and Streeter's original definition, an orthographic neighbor is a word with the same number of letters that differs from the original word by only one letter. For instance, the neighbors of the word *read* include *bead*, *road*, and *real*, etc. Fast and efficient word recognition depends on the structure of the mental lexicon and the relationship between form-similar words, which are also referred to as neighbors. Previous research has shown that words having many neighbors produce different behavioral and electrophysiological patterns than words having fewer neighbors (Andrews, 1997; Van Heuven et al., 1998). In lexical decision tasks, words tend to induce faster responses than pseudo-words (Braun et al., 2006; Holcomb et al., 2002).

The multiple read-out model (Grainger & Jacobs, 1996) claims that words from high-density orthographic neighborhoods induce high levels of global lexico-semantic activity, which is why the 'word' response is faster. On the contrary, words from low-density orthographic neighborhoods cause less lexico-semantic activity, which results in slower responses, since the participant needs more time to identify the letter string. At the same time, Coltheart et al. (1977) found in their lexical decision experiment that orthographic neighborhood had no effect on 'yes' responses, but had a large inhibitory effect on 'no' responses. In other words, it took longer for participants to reject non-words with more than with fewer neighbors. This was later confirmed by Sears et al. (1995) and Carreiras et al. (1997), who proved that in lexical decision tasks, target words having many orthographic neighbors resulted in faster and more correct 'word' responses, but slower and fewer correct 'not a word' responses.

Neighborhood density is a significant factor in the neurological aspects of the recognition of pseudo-words, more precisely, in the N400. Pseudo-words cause greater amplitude N400s than words due to the co-activation of orthographic neighbors (Meade et al., 2019). This is due to the fact that when a word appears on the screen, the reader can recognize it, and the neighbors are inhibited. However, when a pseudo-word is presented, neighbors remain activated.

Frequency also affects recognition. Words with high frequency elicit shorter reaction times than those with low frequency, just like high-density neighborhoods elicit faster recognition than words from low-density neighborhoods (Lim, 2016). In bilingual word recognition, the study of interlingual homographs can demonstrate the importance of frequency. In the case of orthographic neighborhood density, participants tend to choose the language that has more orthographic neighbors. For example, in terms of English and Hungarian, the interlexical homograph *rest* (which means 'slothful' in Hungarian) has different frequency rankings according to the languages (368 in English and 37812 in Hungarian). As for its neighbors, in English it has many more (e.g. *reed, best, west, test, nest*, etc.), while in Hungarian – very few orthographic neighbors (e.g. *rost*). Participants are more likely to identify the word as English in this case (Lim, 2016; Marian et al., 2012). This is because words that have high orthographic neighborhood density cause greater lexico-semantic activity as opposed to the low orthographic neighborhood density ones. As a consequence, efficient and effective word recognition depends on both word frequency and orthographic neighborhood density.

1.6. The relationship between handedness and brain lateralization

Handedness reflects the structure of our brain, more specifically its asymmetry. While the left hemisphere controls right-handedness, the right hemisphere controls left-handedness.

In most cases, the left hemisphere is responsible for language-related perception and production as far as dominance is concerned. However, in some cases, the right hemisphere can also be dominant, which initiates the question of its freedom. As there are numerous examples of left-handed people having their right hemisphere dominant in language use (Loring et al., 1990; Rasmussen & Milner, 1997; Vargha-Khadem et al., 1985), it seems more righteous to claim that this freedom is limited to certain features, thus emphasizing the fact that there must be a correlation between language dominance and handedness.

The 'Broca rule' suggests the concept of left-handers having a dominant right-hemispheric dominance based on the overgeneralization of the description of the typical example of the left-hemispheric dominance of right-handers. However, language, alongside dexterity, is able to shift to the right hemisphere and left-handedness is neither a precondition, nor a necessary consequence of right-hemisphere language dominance (Knecht et al., 2000; 2002). Mazoyer et al. (2014), in their research with 297 participants (153 left-handed) came to conclusion that the concordance between hemispheres for handedness and language is not always straightforward. What can be taken for granted is that the dominant hemisphere for language cannot be absolutely determined by one's preferred handedness; other individual factors have to be taken into consideration (Ocklenburg et al., 2014; Somers et al, 2015; Willems et al., 2014).

1.7. The present study

The present study seeks to investigate phonological awareness and the temporal characteristics of bilingual visual word recognition. Studies concerning visual word recognition of bilinguals are essential, on one hand, because of the increasing number of bilingual students in monolingual schools, on the other hand, to raise the consciousness of teachers about this process. Word recognition patterns of orthographically related languages (e.g. English and Dutch) are presumably the same on lower levels (orthographic and phonological), but at higher cognitive levels, in semantics, recognition is strongly language-specific. In orthographically unrelated languages (e.g. Hungarian and Chinese), language-specific characters help the recognition process with the language decision. The two languages investigated in this study have the Latin alphabet. The majority of letters are identical, but there are some language-specific letters with diacritics in Hungarian, which makes it easy to recognize Hungarian words at the orthographic level. However, in words lacking language-specific characters, phonological awareness is important in the word recognition process.

For this study, the following research questions were formulated: (i) What are the temporal characteristics of word recognition?; (ii) Does word recognition require phonological awareness?; (iii) What are the ERP characteristics of visual word recognition?; (iv) Does the recognition of English-like and Hungarian-like pseudo-words trigger the same activation patterns?

Our hypotheses are as follows: (i) the recognition of non-words is faster than that of words; (ii) phonological awareness helps word recognition; (iii) the recognition of real words is faster than that of pseudo-words; (iv) word recognition activates different parts of the brain from the onset of the stimulus to the identification of the word.

2. METHODS

2.1. Participants

Twenty-three Hungarian–English bilingual volunteers (10 males, mean age: 24.57 years, 19 right-handed) were tested in an EEG laboratory. All of them were native speakers of Hungarian with C1 level English proficiency, and they all use English at work and in their everyday lives. They spend at least half an hour a day reading English books and articles. The majority actively uses English for several hours a day on average. None of the participants have lived in an English-speaking country for longer than 3 months. They come from Hungarian monolingual families and use Hungarian at home. All of them are late bilinguals; they started acquiring English in an instructed way at primary or secondary school (mean age of onset 9.97). They all had normal or corrected-to-normal (glasses or contact lenses) vision, no hearing impairment, language disability, learning disability, or any history of neurological illness was reported.

2.2. Procedure

The study with all of its procedures was approved by the Local Ethics Committee. Before the test, a consent form along with the instructions was handed to each participant, and they had to sign it. Participants were informed that the experiment takes approximately one hour, it is non-invasive, which means that it does not cause physical pain or inconvenience, and they can interrupt the experiment at any time without any consequences.

Before the EEG experiment, participants filled in a non-standardized language background questionnaire related to their Hungarian and English language use. They also completed a standardized questionnaire (Language Experience and Proficiency Questionnaire – LEAP-Q), in which they had to list all the languages they know in order of dominance, list all the languages they know in order of acquisition, list the percentage of time they currently and on average are exposed to each language, whether they have lived abroad for a longer period of time, etc. (Marian et. al., 2007).

Participants were asked to minimize any kind of movement during the test in order to diminish the noisiness of the data.

2.3. Test materials

2.3.1. Lexical decision test 1

The lexical decision test contained 30 Hungarian (e.g. *baráti, főutca, nevező*), 30 English 6-letter words (e.g. *decide, option, secure*), and 60 non-words (e.g. *ddddal, iiaauu, mujkkk*). Non-words were created by randomly putting letters together in a way that they could not structurally resemble any meaningful words in either language (i.e. without orthographic neighbors). The participants' task was to decide whether the letter string they see on the screen is a word or not.

2.3.2. Lexical decision test 2

This modified version of lexical decision test included 60 Hungarian (e.g. *batéra, régide, sórami*) and 60 English 6-letter pseudo-words (e.g. *ackone, cutony, maxidy*), and their structures matched with either the Hungarian or the English phonotactic rules. The participants' task was to decide by clicking on the left (English) or right (Hungarian) buttons of the computer mouse, which of the presented letter strings would suit the Hungarian and which the English language. With this test, we checked the phonological awareness in the two languages.

2.4. Stimulus presentation and EEG recording

A previously designed custom-made program written in MATLAB (MatLab Inc.) with the Psychtoolbox extension (Kleiner et al., 2007) running on a PC was used for the experiments (Navracsics & Sáry, 2013). Stimuli were presented on a white background, using black characters in the middle of the screen. The viewing distance was set to be the appropriate normal viewing distance of a computer screen (~ 50 cm). Trials started with the onset of a fixation spot in the middle of the screen, which was followed by a stimulus chosen from the pool. The inter-trial interval was 1 s, the stimulus stayed on the screen for 2 s (exposure time). During this time participants were requested to hit the right or left button according to the task instructions. Failure to respond in the time window resulted in the continuation of the task to the next trial. The task was machine paced to ensure a constant level of attention from the participants. The program recorded correct/incorrect hits and response latency times. Neural activity was recorded with a 128-channel EEG system (Biosemi).

2.5. Data analysis

Incorrect responses were excluded from analyses. Response times per condition were averaged separately for participants and the mean samples were compared with T-tests.

The EEG data were preprocessed by re-referencing to the average of all channels, removing line noise with a band-stop filter around 50Hz and band-pass filtering with a 0.5-30 Hz FIR filter. Eye movement artifacts were removed by manually observing and excluding noisy ICA components. Next, stimulus-locked epochs were extracted from -1 s to 2 s around stimulus onset time. Epochs were baselined to the mean amplitude in the -200-0 ms pre-stimulus window, and finally averaged in each channel to obtain ERP waveforms.

Data from each participant was processed individually, and group-level analysis took place with the FieldTrip toolbox in MATLAB. The data were compared between the critical conditions in both experiments (words vs. non-words; Hungarian-like vs. English-like pseudo-words). To identify significant differences in the grand averaged ERP waveforms, we used a dependent samples T-test with permutation-based cluster correction (1000 Monte-Carlo permutations) across all channels in the 100-600 ms time window. In this correction method, data points are analyzed in the context of their neighbors in the time and location dimensions. Clusters of significant t-statistic ($p < 0.05$) were considered truly significant if the cluster size exceeded 97.5% of the randomly permuted cluster sizes.

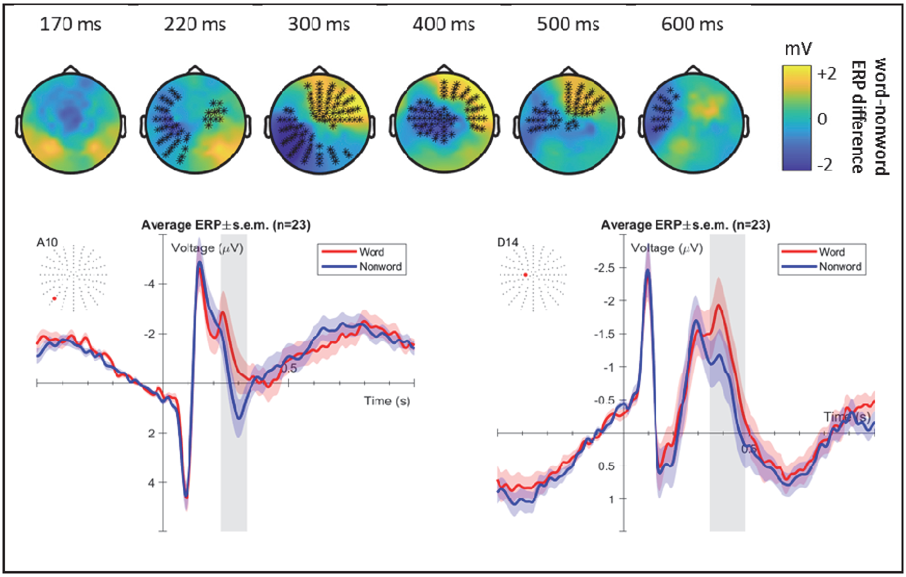
3. RESULTS

3.1. Words and non-words

Figure 1

Topoplots representing the ERP difference between words and non-words at denoted times. Channels with significant contrast are denoted by asterisks ($p < 0.01$). (Bottom) ERP waveforms at the left occipital A10 (left panel) and the central D14 (right panel) channels. The shading represents times of significant difference ($p < 0.05$).

Topografski prikaz koji predstavlja razliku kognitivnih evociranih potencijala između riječi i neriječi u određenoj vremenskoj točki. Kanali sa značajnim kontrastom označeni su zvjezdicom (p < 0,01). (Dolje) Oblici valova kognitivnih evociranih potencijala na lijevom okcipitalnom A10 (lijevi prikaz) i centralnom D14 (desni prikaz) kanalu. Sjena predstavlja vrijeme statistički značajne razlike (p < 0,05).

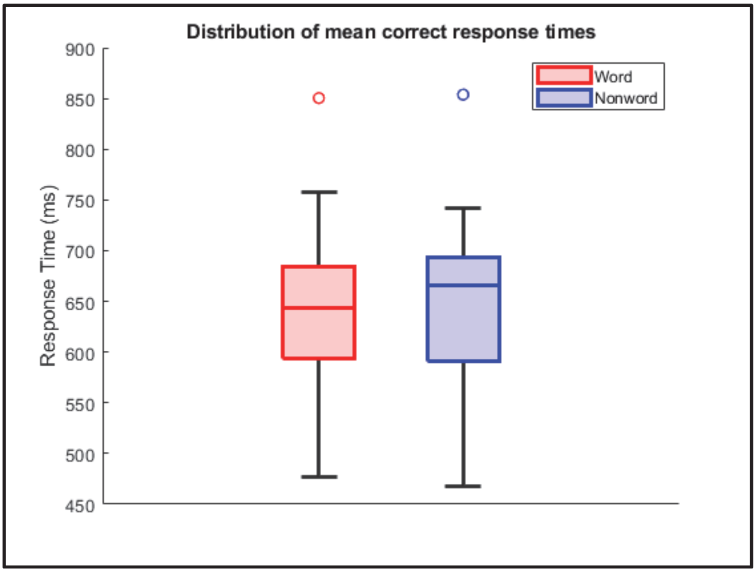


The ERP waveforms do not seem to differ in the first 200 ms, then they start to diverge in multiple regions (Fig. 1. Top). The earliest differences between word and non-word processing are apparent in the late parts of the N170 component around 220 ms. This can be observed as a clear second peak in the late N170 (Fig. 1. Bottom left). The central N400 component is more pronounced for the word condition (Fig. 1. Bottom right). A cluster of right frontal negativity can also be seen in the results but this cannot clearly be linked to any well-described ERP components, thus we omit its detailed description.

Figure 2

Distributions of correct response time means across participants in the first experiment. The boxes display the median, lower, and upper quartiles, and the whiskers reach to the non-outlier minima and maxima. Outliers are defined as data points that are at least 1.5 inter-quartile range from the top or bottom of the boxes.

Distribucija prosječnog vremena davanja točnih odgovora za sudionike u prvom eksperimentu. Okvir prikazuje medijan, donje i gornje kvartile, a crte dopiru do minimalnih i maksimalnih vrijednosti. Netipične vrijednosti označene su kao podatkovne točke koje su najmanje 1,5 interkvartilnog raspona udaljene od vrha ili dna okvira.



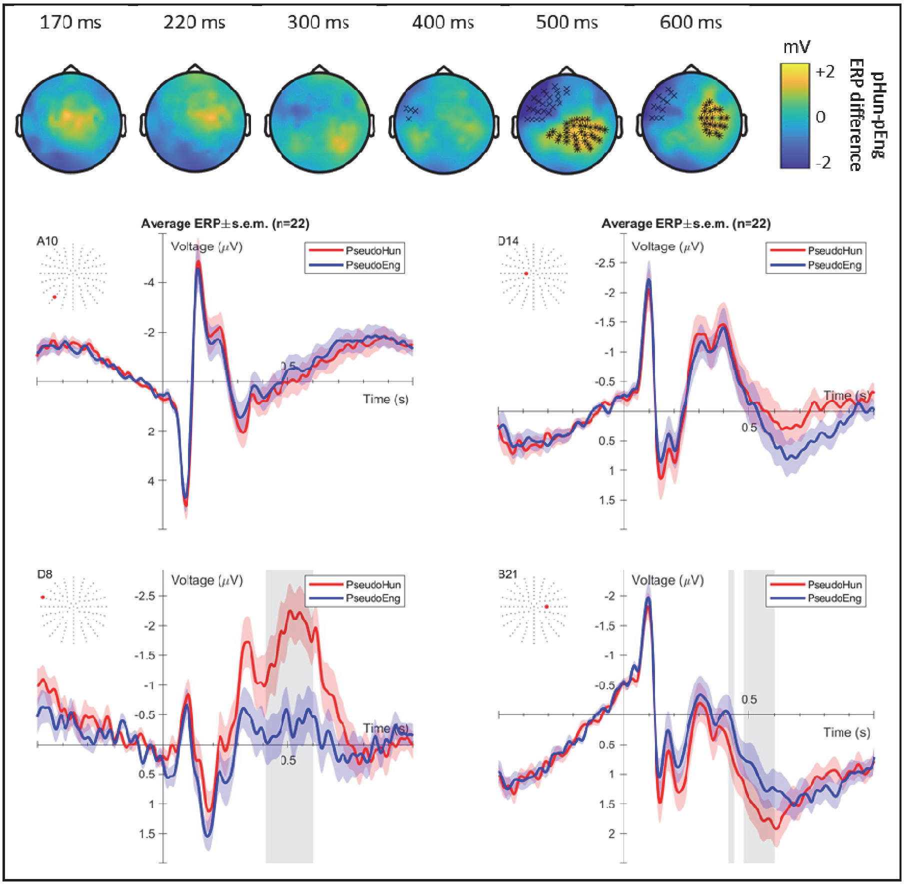
The group mean response times were 649 ms and 648 ms for the Word and Non-word conditions respectively (Fig. 2.), and the difference was clearly not significant.

3.2. English-like and Hungarian-like pseudo-words

Figure 3

Topoplots representing the ERP difference between Hungarian-like and English-like pseudo-words at denoted times. Channels with significant contrast are denoted by crosses ($p < 0.05$) and asterisks ($p < 0.01$). (Middle) ERP waveforms at the left occipital A10 (left panel) and the central D14 (right panel) channels. (Bottom) ERP waveforms at the left temporal D8 (left panel) and the right central B21 (right panel) channels. The shading represents times of significant difference ($p < 0.05$).

Topografski prikaz predstavlja razliku kognitivnih evociranih potencijala između pseudoriječi sličnih mađarskome i onih sličnih engleskome jeziku u određenoj vremenskoj točki. Kanali sa značajnim kontrastom označeni su križićem ($p < 0,05$) i zvjezdicom ($p < 0,01$). (Sredina) Oblici valova kognitivnih evociranih potencijala na lijevom okcipitalnom A10 (lijevi prikaz) i centralnom D14 (desni prikaz) kanalu. (Dolje) Oblici valova kognitivnih evociranih potencijala na lijevom temporalnom D8 (lijevi prikaz) i centralnom B21 (desni prikaz) kanalu. Sjena predstavlja vrijeme statistički značajne razlike ($p < 0,05$).

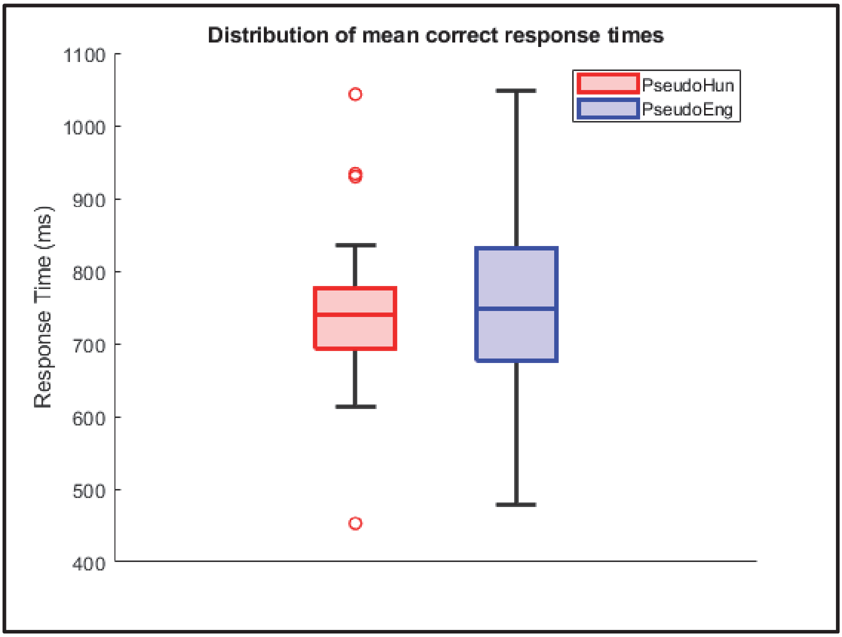


Compared to the previous experiment, the ERP waveforms elicited by pseudo-words resemble that of real words, in that the late N170 and the N400 components are more pronounced than for non-words (Fig. 3. Middle). In these occipital late N170 and central N400 components, we do not find any differences between Hungarian-like and English-like pseudo-words. We can, however, find significant differences later at the left temporal and frontal electrode sites around 500 ms post-stimulus onset (Fig. 3. Top and Bottom left). Perhaps this reflects the activation of the articulatory network (left inferior frontal area), checking the pseudo-words for pronounceability, producing more negative signals for Hungarian-like items.

Figure 4

Distributions of correct response time means across participants in the second experiment. The boxes display the median, lower, and upper quartiles, and the whiskers reach to the non-outlier minima and maxima. Outliers are defined as data points that are at least 1.5 inter-quartile range from the top or bottom of the boxes.

Distribucija prosječnog vremena davanja točnih odgovora za sudionike u drugom eksperimentu. Okvir prikazuje medijan, donje i gornje kvartile, a crte dopiru do minimalnih i maksimalnih vrijednosti. Netipične vrijednosti označene su kao podatkovne točke koje su najmanje 1,5 interkvartilnog raspona udaljene od vrha ili dna okvira.



The group mean response times were 743 ms and 763 ms for the Hungarian-like English-like pseudo-words respectively (Fig. 4.). Apparently, the latter condition is 20 ms slower on average than the former, however, the T-test has found that this difference is not significant ($p = 0.62$). The quicker tendency for Hungarian-like strings could be explained by the presence of language-specific letters (e.g. vowels with accents, such as á, é, í, ó, ö, ő, ú, ü, ű).

4. DISCUSSION

The present study investigates the phonological awareness of bilinguals and the temporal characteristics of written word recognition. The study also explores the time-line of processing phonological information in the recognition of Hungarian and English words, non-words, and pseudo-words. It seeks to discover the temporal characteristics of recognition at the orthographic, phonological, and semantic levels of processing.

In the recognition of words and non-words, ERP waveforms do not differ in the first 200 ms. ERP curves separate from each other in the late parts of the N170 component around 220 ms, hinting at marked differences in later periods of orthographic processing. Based on the pronounced N400, we suspect that word recognition requires greater cognitive activity, which supports the hypotheses related to the reaction time (Navracsics & Sáry, 2013). Non-words are recognized more easily in terms of perceptual processing speed and visual short-term memory capacity (Starrfelt et al., 2013).

When deciding on the perceived language of pseudo-words, occipital late N170 and central N400 components do not show any significant difference between Hungarian-like and English-like strings. A significant difference can only be observed at the left temporal and frontal electrode sites around 500 ms post-stimulus onset. These electrical signals and also the increased reaction times compared to the first experiment indicate that participants need quite a huge cognitive effort to decide which language the pseudo-words belong to; however, phonological awareness could play a key role in helping them with the decision. The results might be interpreted similarly to what Hagoort et al. (1999) suggest in their study that it is the left inferior frontal gyrus (projecting to frontal-temporal electrode sites) that is involved in the sublexical decoding of orthographic input letter sequences into phonological output codes. Although it takes longer for participants to recognize pseudo-words than real words, in the case of highly proficient bilinguals pre-lexical activation helps word recognition. Rodríguez et al. (2022) having similar results claim that higher L2-exposure bilinguals can process L2 more automatically.

When we examined the recognition of words vs. non-words, the response times are relatively fast (649 ms and 648 ms, respectively), and this is underlined by the fact that the ERP waveforms differ as early as 220 ms post-stimulus onset. On the contrary, for pseudo-words, the responses are delayed. Significant difference occurs only at around 500 ms at the left temporal and frontal electrode sites. Pseudo-words elicit pronounced N400s due to the co-activation of orthographic neighbors, as was found similarly in Meade et al. (2019). Whenever a real word appears on the screen, recognition is quick and successful because its neighbors are inhibited. Although, in the case of pseudo-words, the language-specific letter string activates the appropriate language (Singleton, 1999), but neighbors are not inhibited, which leads to a longer reaction time. The Bilingual Interactive Activation+ (BIA+) model (Dijkstra and Van Heuven, 2002) describes this process. The model contains two subsystems, the word identification subsystem (linguistic context), and the task/decision subsystem (non-linguistic context). In the word identification subsystem, the input is processed on the level of sublexical orthography and phonology, and then on the level of lexical orthography and phonology. In this subsystem, the sublexical orthography and the sublexical phonology are in continuous interaction with each other. Then the information is forwarded to the next level, where the lexical orthography and lexical phonology are in connection, as well. The model is interactive, since there is transparency between the subsystems, and the information can be sent back to the previous subsystem to confirm. When the appropriate language is chosen, the semantics of the word is checked. The task/decision subsystem receives the input from the identification system, where the correct language is identified and gets activated (Dijkstra & Van Heuven, 2002). Pseudo-words carry the phonotactic characteristics of a language, but do not carry a meaning. This is why it takes longer to identify pseudo-words than words, as the processing goes on longer without reaching a semantic target. In the case of the recognition of English and Hungarian pseudo-words, reaction time is longer in the recognition of L2 pseudo-words, since participants' language decision strategy depends on their phonological awareness and changes due to the insecurity of their second language (Vargha, 2010).

Our results coincide with the findings of Carreiras et al. (2013) as during visual word recognition, different parts of the brain get activated from the onset of the stimulus. At 100 ms, the visual cortex gets activated, and the visual system responds to the letter strings. Although there is high-level linguistic information processing at this level, the visual system responds only to the frequency of letter strings, and the lexical-phonological and lexical-semantic processing takes place much later. N170 reflects the neural processing of words. This is where the identification of lexical entries takes place. N170 is a response that makes a difference between words and non-words or pseudo-words, as found in Maurer et al. (2005). N400 is associated with lexical-semantic processing that activates word processing (Laszlo & Armstrong, 2013).

As our results suggest, phonological awareness is indispensable for sub-lexical word recognition processes, i.e. for the ability to identify if a letter string is a word or non-word, or if it is an English or a Hungarian pseudo-word. Our results also prove that phonological awareness is a necessary pre-reading skill, since there is a significant difference between the recognition of words and non-words at the early phase of word recognition (220 ms) at the occipito-temporal electrode sites, which indicates that non-sense letter strings can be identified immediately after the stimulus onset. In terms of reaction time, there is no significant difference between the recognition of English and Hungarian pseudo-words, which supports the idea of highly proficient bilinguals having equally high phonological awareness in their two languages.

5. CONCLUSION

Our results suggest that word recognition activates different parts of the brain from the moment of the stimulus onset until the identification of the word, and confirm the hypotheses related to the neurolinguistics and temporal characteristics of bilingual visual word recognition. During visual recognition of words, non-words, and pseudo-words, not only word frequency and familiarity, but also grapheme-phoneme consistency is an influencing factor. Although Hungarian and English have different writing systems, and they are typologically unrelated languages, the language-specific letter strings immediately activate the appropriate language and the recognition patterns are identical in the two languages. Our findings suggest that participants in both linguistic subsystems rely on phonological processes, which proves the hypothesis that phonological awareness has an important role in visual word recognition, and it is a precursor skill to successful reading.

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Fonološka svjesnost dvojezičnih osoba u vizualnom prepoznavanju riječi

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Ovaj rad u kojemu se istražuje fonološka svjesnost dvojezičnih osoba i vremenska obilježja prepoznavanja pisanih riječi testom mješovite leksičke odluke dio je opsežnijega istraživanja. Cilj je rada prikupiti informacije o vremenskim obilježjima prepoznavanja riječi na ortografskoj, fonološkoj i semantičkoj razini obrade. U radu se istražuju obrasci kognitivnih evociranih potencijala (engl. *event-related potentials - ERP*) tijekom prepoznavanja riječi, pseudoriječi i neriječi u mađarskome kao prvom (J1) i engleskome kao inom (J2) jeziku. Dvadeset troje ispitanika dvojezičnih u mađarskome i engleskome jeziku ispitani su u laboratoriju uporabom EEG-a. Svi ispitanici vladaju engleskim na razini C1 i njime se redovito služe u poslu i svakodnevnom životu. U zadatcima leksičke odluke komponente N170 (lijeve temporalne elektrode) i N400 (centralne elektrode) bile su izraženije u pokušajima prepoznavanja riječi od prepoznavanja neriječi. Ta aktivnost vjerojatno odražava integracijske procese i procese povezivanja značenja tijekom prepoznavanja riječi. U zadatcima jezične odluke za pseudoriječi, niz koji je sličan mađarskome jeziku elicitirao je kasnu (300-600) negativnu komponentu na strani lijeve frontalne elektrode, što se nije pokazalo u kognitivnim evociranim potencijalima za pseudoriječi slične engleskim riječima. Valja istaknuti da je zadatak bio drugačiji u dvama eksperimentima, što je vjerojatno utjecalo na obradu stimulusa, kao i na elicitirane oblike valova kognitivnih evociranih potencijala. U zadatcima jezične odluke fonološka svjesnost ima ključnu ulogu te doprinosi uočenim razlikama.

Ključne riječi: *EEG, kognitivni evocirani potencijali, dvojezična leksička odluka, vizualno prepoznavanje riječi, fonološka svjesnost*