Doctoral (PhD) Dissertation Booklet

Event-Related Potentials in the Study of Hungarian-English Bilingual Visual Word Recognition

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Introduction

The study of individual bilingualism has a relatively short history that goes back to the onset of infant bilingual development research in the 1990s, following the study of the bilingual mental lexicon with different psycholinguistic tests, and finally, mapping up the structure and function of the bilingual brain with a neurolinguistic approach using neuroimaging procedures. Each and every bilingual individual experiences a particular language acquisition pattern, and they use their two languages in their everyday lives on a daily basis, with different people in different situations, and on different topics (Grosjean, 1982). The diversity of perspectives and different linguistic settings contributed to the increase in bilingual research.

The literacy development of bilinguals is a worldwide issue, since the number of bilinguals (and multilinguals) is emerging. Studies on bilingual processing at the word level are important, as teachers could get a better understanding of how bilingual word recognition takes place and what reading and processing difficulties bilingual students may have.

Word recognition includes all mental activity from the perception of the word to the identification of its lexical representation that is available in the mental lexicon. Studies in bilingual written word recognition intend to find out whether a written word leads to the activation of both linguistic subsystems or whether the activation is restricted to the contextually relevant subsystem of the bilingual memory (De Groot, 2011). Lexical decision test results cover a wide range of information about visual word processing. With an electrophysiological (EEG) study the 'what', 'when', 'where', and 'how' can be revealed in visual word recognition (Carreiras et al., 2013). In lexical decision tasks, letter strings are presented and participants decide whether the letter strings are words or not while response latencies and accuracy are measured.

Research Aim, Significance, and Scope

The present paper draws attention to the significance of how bilinguals might differ from monolinguals, and how their (language) learning strategies and word recognition patterns differ from each other. In opaque (deep) orthographies, writing systems do not have a one-to-one correspondence, which indicates that the reader must acquire the peculiar or arbitrary pronunciations of words. With transparent (or shallow) orthographies, the spelling-sound correlation is clear: one can pronounce a word correctly by following the rules of pronunciation. It means that words are spelled consistently and have a one-to-one relationship between their graphemes and phonemes. Readers who first learned to read opaque morphosyllabic orthography use less sublexical phonology while reading in the second language than do other second language learners, which helps the learning processes (Borleffs et al., 2017). Meanwhile, readers who learn transparent orthography for the first time rely more on the features of sublexical phonology, which makes learners less susceptible for teaching (Bhide, 2015). Depending on the word type, the surrounding context, and the individual's literacy experiences, reading strategies, reading speed and accuracy might vary. There is an understanding that literacy experiences, including which language a person learns to read in first and how they are taught to read, can have significant effects on the further reading processes. People who learn to read a more transparent orthography tend to depend less on morphological and orthographic information and more on sublexical phonology (Bhide, 2015).

Words are basic units of language that are found in both spoken and written language. Reading requires the perception of the printed word, which is a fundamental ability. Although the identification of printed words is frequently studied in monolingual situations, bilingual written language processing remains an unexplored topic, particularly 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. Research on visual word recognition of bilinguals is fundamental, since numerous bilingual students attend monolingual educational institutions, and teachers have to be aware of what is happening in a bilingual student's mind when they are facing reading or writing exercises, since they have to cope with two languages.

The research goal of this paper is to gain information about the temporal characteristics of recognition at the orthographic, phonological, and semantic levels of processing. The research questions concern the temporal characteristics as well as the ERP components of isolated bilingual word recognition process.

Methods

Twenty-three Hungarian–English bilingual volunteers (10 males, mean age: 24.57 yrs, 19 right-handed) were tested in an EEG laboratory. The study was approved by the Ethics Committee. When choosing the participants, I focused on homogeneity. All of them are Hungarian native speakers with C1 level English proficiency, and use English at work or in their studies 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 acquired English in an instructed way at primary or secondary school (mean age of acquisition is 9.97 years). 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.

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.

The language decision test included 180 monosyllabic words: 60 Hungarian (e.g. *bál, cím, lyuk*), 60 English (e.g. *age, cat, hair*) and 60 interlexical homographs (words with identical spelling but different meanings in the two languages) (e.g. *comb, hold, mind*) and cognates (words with identical spelling and same meaning in the two languages) (e.g. *blog, film, lift*). Participants were asked to make decisions whether the word on the screen is Hungarian or English and click on the left (English word) or right (Hungarian word) button of the computer mouse. Words appeared on the screen in a mixed, pseudorandom order to keep participants' both languages active. With this experiment, I checked language activation.

The lexical decision test contained 30 Hungarian (e.g. *ajánló, ebédlő, hegedű*), 30 English 6-letter words (e.g. *abroad, casual, option*), and 60 non-words (e.g. *eekkff, ggggss, paaars*). The participants' task was to decide whether the letter string they saw on the screen was a word or not. With this test, I checked the word superiority principle.

The modified version of the lexical decision test included 60 Hungarian (e.g. *amagyi, erédes, marisó*) and 60 English 6-letter pseudo-words (e.g. *bliney, foreet, rapoon*), and their structures matched with either the Hungarian or the English phonotactic rules. The participants' task was to decide which of the presented letter strings would suit the Hungarian and which the English language. With this test, I checked the phonological awareness in the two languages.

A previously designed custom-made program (Navracsics & Sáry, 2013) written in MATLAB (MatLab Inc.) with the Psychtoolbox extension (Kleiner et al., 2007) running on a PC (Asus, UX303UB) was used for the experiments. Stimuli were presented on a white background, using black characters (Arial, font size 14) in the middle of the screen (display resolution 1920 x 1080). 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 set for 1 second, the stimulus stayed on the screen for 2 seconds (exposure time). During this time participants were requested to press the right or left button according to the task instructions. Failure to respond within the allocated time interval 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). Incorrect responses were excluded from analyses. Response times and response languages were averaged separately per condition for each participant 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 second to 2 seconds 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 each experiment. 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.

Results

The behavioral analysis of the language decision test suggests that there is high accuracy for both Hungarian and English conditions, however, homographs indicated a bias towards English responses. Mean correct response times were 768 ms, 772 ms, and 922 ms for the Hungarian, English, and homograph conditions respectively. The comparison of homograph response times based on decision language revealed a difference between Hungarian and English responses. Hungarian responses took on average 995 ms, whereas for English they took 916 ms, a difference that proved to be significant.

The ERP analysis of non-homographs reveals that between 100 and 300 ms (orthographic-phonological level) there is no significant difference between the Hungarian and English conditions. Significant difference can be found between 320 and 520 ms in the central region (lexico-semantic processing). In the case of homographs, there is no significant difference between languages, which suggests that processing homographs does not trigger different processing patterns.

In the case of the lexical decision test, the group mean response times were 649 ms and 648 ms for the Word and Non-word conditions respectively. Significant difference between the two conditions occur at the early phase of word recognition (200-350 ms) at the temporal electrode sites, and at 350-500 ms in the central regions. Central parts of the brain show higher brain activity in the case of words than non-words, which means that the recognition of real words requires greater cognitive activity. This explains that semantics has a role in visual word recognition.

The modified lexical decision test reveals that the group mean response times were 743 ms and 763 ms for the Hungarian-like and English-like pseudo-words respectively. Compared to the previous tests, the temporal aspect of word recognition in delayed. Significant difference occurs only at 420 ms at the frontal electrode sites.

Discussion

This thesis offers a review of the most relevant results achieved in the field of neurolinguistics and psycholinguistics. It also analyses cognitive neuroscience studies examining bilingual word recognition. The paper uncovers the effects of bilingualism on the phonological, lexico-semantical aspects of language processing, as well as how age of acquisition and proficiency influence language processing in different brain areas. It also seeks to find out whether the language neural network differs between first and second language processing. I conducted a comprehensive evaluation of research that used neuroimaging methods to investigate the effects of bilingualism on brain structure, function and connectivity.

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 paper have 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.

While 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. Hungarian and English are typologically non-related languages. In the case of bilinguals, who speak two typologically unrelated languages, the language-specific letter string immediately activates the appropriate language, since the other language lacks that combination of letters (Singleton, 1999). In this study, in the case of highly proficient bilinguals the recognition of the two languages has the same activation patterns. These results correspond with other researchers' results gained from investigations on typologically related languages, such as Spanish-English (Macizo et al., 2010; Schwartz et al., 2007), or Dutch-English (Lemhöfer & Dijkstra, 2004; Van Assche et al., 2009), which suggests that typology does not influence word recognition.

Results also show that word recognition activates different parts of the brain from stimulus onset to word identification, confirming hypotheses about the neurolinguistic and temporal characteristics of bilingual visual word recognition (Navracsics & Sáry, 2013; Carreiras et al., 2013; De Groot, 2011). On the orthographic-phonological level, there is no significant difference between Hungarian and English word recognition. It means that participants did not have to put in any extra effort to identify the words, implying that word familiarity is important in visual word recognition, as claimed by Assadollahi and Pulvermuller (2003), Dambacher et al. (2006), and Yum and Law (2021).

I found that the responses to unambiguous words were equally fast and accurate for both Hungarian (L1) and English (L2) items. However, the responses slowed drastically (~150 ms) for homograph words, and showed a bias towards English responses, despite on average the homograph items were equally frequent in both languages. Although the variation in the response language can be partly explained by the relative frequency between the two languages, the skewed nature of the homograph responses is clear, showing a bias towards English.

The reaction times for homograph items were found to be slower for Hungarian responses, in line with the findings of Navracsics and Sáry (2013). This seems to agree with the previously mentioned response bias, an advantage of English over Hungarian. The two effects line up nicely, with a correlation between the decision language preferences and the time cost of Hungarian responses. I suggest that this bias is indicative of the underlying strategy that participants developed during the experiment.

The ERP results might support this strategy theory, showing a more pronounced N400 component for Hungarian words, than for English. The N400 is widely understood as a surprise signal, having higher amplitudes for unexpected stimuli. I propose, that the more negative N400 could be a sign of mismatch between the expected language and the actual language of an item. Since the homographs could apparently easily be seen as English, they met the criteria of the expectation, hence the in-between N400 component.

Alternatively, the elevated N400 could also be a sign of more rich semantic representations and neighborhoods for Hungarian words. I argue, however, that this is less likely, since the homographs had an equally high frequency in the Hungarian corpus, as the non-homograph Hungarian words; if the recognition is invariant to language expectation, then these words should also show an N400 at least as prominent as the Hungarian ones.

The lack of any early differences between the ERP waveform shows, that the first stages of word recognition do not differ for Hungarian, English and homograph words, or at least not in this experiment. This might be due to both of them being Latin-based scripts, requiring similar processing steps (perhaps N200 differences would arise when comparing alphabetic scripts to syllabaries, or left-to-right writing systems to right-to-left ones). The most obvious visual difference between Hungarian and English scripts is the absence of diacritics in the latter. This, apparently, is not enough to elicit a large-scale neural difference, detectable with ERP.

Based on the visual word recognition models, the conclusion can be drawn that both lexicons of a bilingual individual are active (Dijkstra et al., 1999). The processing of interlexical homographs confirms that besides orthographic awareness, phonological and semantic representations are needed to identify a visual word. In case of written word recognition, phonological activation occurs, as it was previously stated in the semantic, orthographic, phonological interactive activation model.

For the co-activation of both lexicons Lemhöfer and Dijkstra (2004) gave the BIA+ model as an explanation. According to BIA+ (Dijkstra and Van Heuven, 2002), the visual presentation of a word leads to parallel activation of orthographic input representations in L1 and L2. Semantic and phonological representations are activated by these representations, and it ends up in a complex interaction between codes. When the appropriate language gets selected, the input word is recognized. Moreover, BIA+ says that interlexical homographs have separate representations for each language. BIA+ furthermore emphasizes that the activation of various lexical representations is continuously audited by the task/decision system, which supports task execution and decision-making (Green, 1998).

The reaction time of the recognition of homographs is slower for bilinguals, since they are exposed to two meanings of homographs. Hsieh et al. (2017) also give the BIA and BIA+ models (Dijkstra and Van Heuven, 1998, 2002; Thomas and Van Heuven, 2005) as an explanation, since all nodes between languages are interconnected at the word level, and they mutually inhibit each other. Slower reaction times for interlexical homographs suggest that bilinguals face a competition of representations from their L1 and L2 during the processing of homographs (Hsieh et al, 2017). The data support language non-selectivity, which means that there is an automatic co-activation of information in both linguistic subsystems.

The response time of homographs is also longer because the processing of written words continues until the orthographic word unit is recognized, and the orthographic representation meets the linguistic properties (phonology, morphology, semantics). According to Carreiras (2013) at this point, the boundary line between orthographic processing and linguistics processing is fuzzy. Nazir et al. (2004) furthermore explain that high-level considerations form the distributional characteristic features of letters in the given language, and the word recognition system learns these properties that make reading successful. Words with high frequency result in perceptual learning that helps fast and effective word recognition, which means that word frequency also influences word recognition (Frost, 2012; Kronbichler, 2004). Neurolinguistic evidence (Simos et al., 2002; Solomyak & Marantz, 2010; Szwed et al. (2012) suggest that although, high-level linguistic information already exists at approximately 100 ms from stimulus onset, the visual system responds only to the frequency of letter strings, and lexical and phonological features are taken into consideration much later. It also explains why the recognition of cognates and interlexical homographs takes a longer time.

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, I 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. 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. I propose that this task activates the left inferior frontal gyrus (projecting to frontal-temporal electrode sites), a part of the brain that is involved in the sublexical decoding of orthographic input letter sequences into phonological output codes as suggested in Hagoort et al. (1999). 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 I examined the recognition of words vs. non-words, the response times are pretty fast, 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).

The 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 the results suggest, phonological awareness is indispensable for sublexical 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 nonsense 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.

Conclusion

Results suggest that parallel activation of Hungarian and English during bilingual visual word processing. The present study provides evidence for co-activation and competition between languages in bilingual word processing. Furthermore, the results illustrate that although Hungarian and English have different writing systems, and they are typologically unrelated languages, processing patterns are very much alike. Although there is always a dominant language, C1-level bilinguals cannot inhibit either of the languages, which leads to the parallel activation of both mental lexicons. The recognition of interlexical homographs does not trigger different processing patterns; however, different cognitive efforts can be observed according to the judgement of languages. The results also 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. My 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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