CUES & RULES - NEUROCOGNITIVE INVESTIGATION OF AUDITORY AND VISUAL PROCESSING OF WORDS

Closing Report of the project No. OTKA NK 101087

Cues and templates in speech - Work package 1. Cross-linguistic comparison of word stress processing

Short summary

One of the main aims of the project was to investigate the role of local and global analysis in processing the incoming linguistic stimuli. In Work Package 1, we addressed the problem of how native prosodic representations influence the processing of language related acoustic information. To answer these questions, we conducted 4 experiments: Experiment 1 investigated the word stress processing difficulty of Hungarian speakers in a behavioural study; Experiment 2 used a cross-modal word fragment ERP priming paradigm to study the neural background of processing foreign stress cues; in Experiment 3a and b, a passive oddball paradigm was applied to investigate the language specific nature of long-term stress representations; and Experiment 4 investigated the neurocognitive background of long-term stress representations, with a special focus on the predictive coding aspect of these representations. Our results can be summarized as follows.

- We found that the stress processing difficulty of Hungarian speakers is persistent: experience with a foreign language in which stress conveys meaning do not alter it. The origin of the difficulty is that speakers of a fixed-stress language are unable to form appropriate foreign language stress representations. However, we also found that the stress processing difficulty does not generalize to implicit aspects of foreign language word recognition.
- Related to the nature of stress representations, we demonstrated that they are language specific, and have a long-term representation influencing the processing of non-native prosodic information.
- Our data collected in fMRI measurements provided novel evidence for the rule-based predictive coding of prosody, and we showed that the processing of word stress is supported by a neural network that involves the posterior superior temporal gyrus bilaterally.

1. Stress deafness: cue- or template-related? (Experiment 1 and 2)

1.1 Experiment 1: Stress deafness study in second language learners

Cognitive components of foreign word stress processing difficulty in speakers of a native language with non-contrastive stress

Stress contributes to the segmentation of continuous speech into words; therefore, the correct perception of word stress in essential in foreign language acquisition. Previous studies consistently showed that the non-contrastive nature of stress in a native language influences how speakers perceive stress pattern, leading to a marked impairment in stress processing termed as stress "deafness" (Dupoux et al., 2001; Dupoux et al., 2008; Peperkamp et al., 2010). Dupoux et al. (2008) also demonstrated that the performance of native speakers of French (a language with non-contrastive stress) on a task that involved the recall of changing stress-

minimal pairs (SRT = Sequence Recall Task) remained low even if they had a relatively high proficiency in a language with contrastive stress (e.g., Spanish). However, these studies left open some questions. First, the effect of learning a language with contrastive stress was investigated only with French participants; therefore, the generalizability of this effect is questionable. Second, the contribution of cognitive factors to the performance on the SRT has not been investigated before, although the SRT puts high demands on working memory (WM). In addition, phonological awareness (PA), the ability to detect and manipulate the phonological units of language, was found to influence L2 pronunciation aptitude (Hu et al., 2013) and L2 word reading (Li & Chen, 2016). Furthermore, inhibitory control (IC), the ability to successfully respond to a task-relevant dimension while suppressing interference due to a task-irrelevant dimension, was found to be superior (Bialystok et al., 2008, 2009) in bilingual children and adults; and thus it is supposed that IC ability contributes to solving L2 tasks (Lev-Ari & Peperkamp, 2013). Therefore, this study investigated the influence of cognitive factors (WM, PA, and IC) and L2 proficiency on the processing of L2 stress using the SRT among native Hungarian speakers learning or not learning German as a second language. In the experiment, in contrast to the original project proposal, participants heard German instead of English stimuli. The reason for this is that in a pilot experiment with English speech material, we found that stress minimal pairs differed not only in the stress related acoustic cues (e.g., intensity, f0), but also in the vowel quality. Therefore, we decided to use German as the target language, because in German the modification of stress do not necessarily influence vowel quality, but at the same time, the placement of stress on the first or second syllables of words is as valid as in English.

Fifty-four native speakers of Hungarian, a language with non-contrastive stress, participated in the study, who were categorized as not speaking German (n = 19) or having a proficiency at the intermediate (n = 17) or advanced level (n = 18).

The experimental task (SRT) was to remember and reproduce sequences of German pseudowords differing in their phonetic (phoneme task: mäge – mäse) or stress structure (stress task: LIdu – liDU; capital letters indicate stress). In contrast to previous studies, we used stimuli with the actual acoustical cues of German, because we assumed that not only the stress pattern but also its acoustical realization is an important factor of stress processing. Cognitive factors measured included working memory (Digit Span), phonological awareness (Phoneme Deletion), and inhibitory control (Stroop Test).

The error data obtained in the SRT as well as the effect of cognitive predictors on SRT performance were analyzed with generalized linear mixed modeling with binomial distribution. The GLMM is a more reliable data analysis method than the ANOVA for binary outcomes (Jaeger, 2008). Results showed that the stress task led to lower performance than the phoneme task, irrespective of L2 proficiency. Our results can be summarized as follows:

- The degree of performance difference between stress and phoneme contrast slightly increased with longer sequences. Furthermore, different cognitive factors contributed to the errors in the tasks. In the phoneme task, WM, PA, and IC contributed to the performance: Weaker IC ability, lower WM, and attenuated speed of PA were related to lower performance. However, in the stress task, it was only the WM and PA but not the IC that had similar modulating effect on performance.
- A persistent stress "deafness" effect characteristic for Hungarian was found, indicating that the impaired processing of stress information remains unchanged even if someone is highly familiar with a language in which the stress contrast is a significant phonological feature.
- Familiarity with the phonetic properties of stress does not help to overcome the stress processing deficit of L2 learners.
- The cognitive components modulating SRT performance over L2 proficiency showed that higher WM and enhanced speed in PA led to lower error rates in both the phoneme and

stress tasks. The appearance of inhibitory control as a predictor only in the phoneme task but not in the stress task is a surprising finding. We assumed that participants with higher IC performed better on the phoneme task by efficiently suppressing the competing L1 phoneme representations in the service of appropriate encoding of the L2 stimulus sequence in short-term memory. In contrast, there were no competing L1-L2 representations in the stress task, because L2 stress cannot be represented accurately; therefore, an IC advantage could not contribute to task performance. Our findings may have important implications in language teaching as they show that speakers of languages of non-contrastive stress may not have the necessary cognitive basis to form proper L2 representations. It means that more emphasis should be put on the suprasegmental phonology of the foreign language taught (English is the very odd).

Status:

Published papers

- Valéria Csépe (2017) The Multilingual Brain – Implications for the Future. In: Simone E Pfenninger, Judit Navracsics (eds.) Future Research Directions for Applied Linguistics. 312 p. Bristol: Multilingual Matters Ltd., 2017. pp. 33-51.
- Kóbor, A. Takács, Á., Honbolygó, F. Csépe, V. (2014) Generalized lapse of responding in trait impulsivity indicated by ERPs. *International Journal of Psychophysiology*, 92: 16-25.

Resubmitted after revision (under editorial decision)

- Ferenc Honbolygó, Orsolya Kolozsvári, Valéria Csépe: Processing of word stress related acoustic information: a multi- feature MMN study. *International Journal of Psychophysiology*

1.2 Experiment 2: Processing of foreign stress patterns and the detection of stressed syllables

Listeners commanding a fixed-stress native language implicitly use free word stress in a second language

The unexpected results found led us to design a new series of experiments. Contrary to the experiment described in the project proposal, we used a completely different paradigm to study the impact of native stress representations on the processing of foreign stress patterns. The experiment was created in cooperation with the laboratory of Claudia Friedrich (University of Tübingen, Germany).

Recent neurocognitive research using event-related brain potentials (ERPs) made it clear that native listeners implicitly use the mandatory stress pattern of their fixed-stress (non-contrastive stress) L1 (Honbolygó & Csépe, 2013; Domahs, Knaus, Orzechowska, & Wiese, 2012). However, listeners with a fixed-stress L1 have difficulties in handling other stress patterns than that of their native language. These findings are captured by the stress "deafness" hypothesis (Dupoux et al., 2001), which also seems to be present in L2 word recognition (Dupoux et al., 2008) At the same time, eye-tracking and priming results show that native listeners and L2 learners with free-stress L1 are able to implicitly use stress variation in word onsets (see Sulpizio & McQueen, 2012). Lexical decision responses, however, are not entirely informative about each aspect of processing that is tapped by the primes. It appears that ERPs reflect facilitated processing of multiple lexical hypotheses more precisely than response latencies (Friedrich, Felder, Lahiri, & Eulitz, 2013). In a cross-modal, auditory-visual word onset priming task with native German listeners, targets that overlapped in stress with their preceding primes elicited an ERP effect starting around 300 ms after target word onset; and they elicited facilitated behavioral responses compared to targets that do not overlap in stress (Friedrich, Kotz, Friederici, & Alter, 2004). Therefore, in this study, we focus on the gap between Hungarian listeners' (fixed-stress L1) implicit sensitivity to their native stress, which implies

that they are able to extract and use stress, and their diminished explicit stress discrimination ability in a free-stress L2. We test whether stress "deafness" generalizes to implicit aspects of word processing in an L2 with free stress (German).
Thirty two native speakers of Hungarian learning German as a second language, performed a cross-modal word onset priming task while EEG was recorded using a high-density (128 channels) electrode net. In order to selectively follow the implicit use of stress during word recognition, we used a paradigm that fully crossed stress overlap with phoneme overlap. The auditory presentation of stressed and unstressed German word onsets (primes) was followed by visually presented versions of initially stressed and initially unstressed German disyllabic words (targets). Prime-target pairs varied across four conditions: (i) overlap in stress and in phonemes ("MAN-MANdel" almond]); (ii) overlap in stress, but not in phonemes ("DOK-MANdel"); (iii) overlap in phonemes, but not in stress ("man-MANdel"); or (iv) overlap neither in phonemes nor in stress ("dok-MANdel"). Both stressed and unstressed primes were used. ERPs were computed time-locked to the presentation of the correctly responded target stimuli and other measures were also administered: a screening questionnaire about the background and details of participants' German language knowledge, a read-aloud task examining their native-like accent, and a linguistic test estimating language proficiency.
Analysis of RTs to correctly responded target words indicated clear phoneme priming (faster RTs for phoneme overlap). The stress priming (faster RTs for stress overlap) was restricted to stressed primes. ERPs reflected the stress priming exerted by both prime types: ERPs were more negative for stress mismatch than for stress overlap over the posterior right electrodes. We did not find any interaction effects between RT/ERP phoneme priming and RT/ERP stress priming. Furthermore, we did not find significant correlations between ERP stress priming and language proficiency or L2 experience measures, but less native-like accent was associated with larger stress priming on RTs for targets following stressed primes.

- The finding that stress priming did not interact with the type of the prime indicates that Hungarian listeners extract stress information from the primes, store the stress pattern of the target word, and match both sources. ERP stress priming started somewhat later than formerly observed in German L1 listeners (Friedrich et al., 2004).
- The later onset of this effect might reflect generally delayed L2 processing in L2 learners compared to native listeners. In contrast to the ERPs, the behavioral stress priming effect differed for stressed and unstressed primes. This might reveal a processing bias towards fixed word initial stress in Hungarian. The partial dissociation of ERP and behavioral results could indicate that the underlying cognitive system considers more lexical candidates than facilitation in the behavioral outcome suggests. It appears that at a relatively late selection stage, which is associated with the lexical decision response, some potential candidates are filtered out, when the implicit knowledge of the mandatory L1 stress might start to play a role.
- In German listeners, behavioral and ERP stress priming did not interact with phoneme priming in this study. Moreover, active Hungarian listeners equaled native German listeners in this basic cognitive architecture of speech processing.
- Our results strengthen the conceptualization of separate processing paths for word stress and phonemes that are linked to separate word form representations for both types of information. These findings altogether show that stress "deafness" does not generalize to implicit aspects of L2 word recognition. Rather, it might relate to the redundant interdependency of the prosodic speech processing path and the phonemic speech processing path in a fixed-stress L1.

Status:
Under revision before resubmission:

- Ferenc Honbolygó, Andrea Kóbor, Valéria Csépe: Cognitive components of foreign word stress processing difficulty in speakers of a language with non-contrastive stress. *International Journal of Bilingualism*

2. Stress templates: Rules in solving cue and template incongruency (Experiment 3 and 4)

2.1 Experiment 3a: Are stress templates language-specific?

Word stress representations are language specific: evidence from event-related brain potentials

In the project proposal, we planned to conduct a cross-linguistic ERP study, in which we wanted to investigate the stress pattern violation using the stress cues of a foreign language. We intended to run the experiment with both Hungarian and German participants; however, the later aim could not be accomplished. Instead, we created another ERP experiment, in which we extended the passive oddball paradigm to investigate the context-related effects of word stress processing.

In our previous studies (Honbolygó et al, 2004, Honbolygó and Csépe, 2013), we proposed a theory about the nature of word stress representation stating that the processing of stress information is based on long-term stress templates, which are speech specific, i.e., they are activated by speech and not by non-speech acoustic stimuli, and language specific, i.e., they are activated by the native language. However, the later hypothesis was not tested. The language-specificity of stress templates would require that the they are not activated by non-native stress cues. In the present project, we investigated this assumption with a cross-linguistic ERP study, in which we studied the stress pattern violation using the stress cues of both the native (Hungarian), and a foreign language (German).

Thirty-two Hungarian participants were presented with a reiterative pseudo-word ('bébé') pronounced either by a Hungarian or a German native speaker, with two different stress patterns: one with stress on the first syllable (trochaic stress pattern, henceforth referred to as S1), and one with stress on the second syllable (iambic stress pattern, henceforth referred to as S2). Speakers were asked to produce the pseudowords as naturally as they could, and no further software editing was done on the recordings. We measured the ERP correlates of processing pseudo-words in a passive oddball paradigm in four experimental blocks: (1) Hungarian S1 standard with Hungarian S2 deviant; (2) Hungarian S2 standard with Hungarian S1 deviant; (2) German S1 standard with German S2 deviant, (3) German S2 standard with German S2 deviant.

As our results show:

- The pseudo-words elicited ERP responses that showed stimulus-related modulations in three time windows. In the early and middle time windows, no MMN was elicited by the Hungarian S1 deviant, while each of the other three deviants elicited the MMN. In the late time window, we obtained a Language x Role interaction, meaning that the stress pattern of the pseudo-word did not affect the late negative component, but whether it was Hungarian or German did.
- These results implied that the processing of stimulus differences were based on long-term language specific stress representations, because only the Hungarian S1 stimulus (i.e., the legal trochaic stress pattern) did not contradict them. All other stimuli differed from them either because of their stress pattern (Hungarian S2), or because of the language (German S1 and S2). Importantly, our results cannot be explained by considering only short term expectations based on the stimulus sequences, because this would require that all four deviants elicit the MMN. Thus, we suggest that – at least in Hungarian – word stress representations are language specific.

Status: The manuscript of this study is in preparation and will be submitted by the end of February

2.2 Experiment 3b: Are stress templates language-specific?

The neural background of language specific prosodic information processing

The aim of the present study was to investigate the language specific aspects of word stress processing. Previous studies investigating the neural background of stress processing demonstrated that the change of stress pattern is processed in an automatic way in disyllabic words as shown by the emergence of the Mismatch Negativity (MMN) ERP component. In the case of trisyllabic words, the situation is more complicated, because there are two possible stress pattern violations, and languages might differ in how listeners process these violations.
Twenty-two native Hungarians participating in the study heard a trisyllabic pseudoword ("fekomot") in a passive oddball paradigm, while we recorded the brain's electrical activity with a 128 channel EEG system. The pseudo-word was spoken by a native Hungarian speaker, and it was recorded with three different stress patterns: stress on the 1st syllable (S1, legal), 2nd syllable (S2, illegal), and 3rd syllable (S3, illegal). The stimuli with three different stress patterns were presented both as standards and deviants in six experimental blocks (with two types of stimuli in each block).
In the case of trisyllabic pseudo-words, we found early and late MMN effects. The early MMN was missing in S1 but it was present in S2 and S3. The lack of MMN in S1 is in line with previous findings showing that pseudo-words with legal stress pattern as deviants do not elicit MMN when contrasted with pseudo-words with illegal stress pattern as standard. The early MMN for S2 and S3 were affected by the context, i.e., the stress pattern of the standard: MMN appeared only when the standard had a legal stress pattern, but there was no MMN when the standard had an illegal stress pattern. ERPs elicited by S2 and S3 were not the same: there were more prolonged negative amplitudes in the case of S3, possibly due to stress appearing later in the case of S3.

- In the behavioural data, we found that the discrimination of S1 and S2 was less accurate than the other pairs, especially when S2 was presented first. We also found an overall increased reaction time when S2 was presented first. This might suggest that S2 is more difficult to retain in working memory during comparison.
- In conclusion, we found that the legal stimulus (S1) could not be violated even in a deviant position, and the illegal stimuli (S2, S3) could not form a reliable memory trace for comparison. This demonstrates that the language-specific stimulus has a long-term representation, strongly influencing the processing of non-native prosodic information.

Status: The manuscript of the study is in preparation and will be submitted by the end of February.

2.3 Experiment 4: the functional neuroanatomical basis of stress processing.

Predictive coding of prosodic features: fMRI evidence

This study investigated the neurocognitive background of word stress processing using functional magnetic resonance imaging (fMRI). The general neural background of regularity coding can be investigated via the repetition suppression paradigm (RSP), in which a decreased neural signal is elicited by the repetition of a stimulus. The present study is the first one to use RSP for investigating stress rule processing with neuroimaging method. Here our aim was to identify brain areas that are sensitive to the violation of stress patterns, using functional magnetic resonance imaging.
Twenty Hungarian participants listened to disyllabic pseudo-words having stress on the first or second syllable. Stimuli were trial unique: 40 different pseudo-words (e.g., "tiki", "divi"), were created, recorded by 4 speakers, and the f0 of the resulting recordings were uniformly

shifted in 3 steps (90, 100, and 110%). Stimuli were presented pairwise. The first stimulus (S1) was either identical to (Repetition Trial, RepT) or different from the second stimulus (S2; Alternation Trial, AltT). In the AltT, the only difference between S1 and S2 was the position of syllable stress: S1 was stressed on the first syllable while S2 was stressed on the second syllable, otherwise the two stimuli were identical. Besides the different trial types, two different types of blocks were presented. In the Repetition Blocks, 70% of the trials were RepTs while 30% were AltTs. In the Alternation Block, 70% of the trials were AltTs and 30% were RepTs. In each block, 20% of the trials were target trials, in which participant had to detect the change of pitch in S2. Target stimuli were created by modifying the fundamental frequency of the original stimuli to 110%, 120%, and 130%. In addition, to determine the putative relevant regions of interests (ROIs) for the analysis of brain imaging data, a functional localizer was created which determined brain areas specific for speech processing and involved three blocks of stimuli (pseudo-words, signal correlated noise, and spectrally rotated speech).

- We successfully identified speech-specific brain areas in continuous MR scanning.
- We found speech specific activity in the posterior superior temporal gyrus (STG), medial STG, and anterior STG bilaterally. Several of these areas showed specific activity to pseudo-word pairs differing in their stress pattern, and the left posterior STG and right medial STG demonstrated the largest repetition probability effect.
- These results provide evidence, to our knowledge the first one, of the predictive coding of prosody, and suggest a specialized neural network that involves the posterior STG bilaterally in the processing of word stress.
- This study was the first one in the MTA RCNS Brain Imaging Centre (to our best knowledge in Hungary in general) that used auditory stimulation delivered by a newly established MR compatible head phone.

Status: The manuscript of the study is in preparation and will be submitted by the end February.

Cues and templates in speech
Work package 2. - Developmental aspects of processing prosodic information

Short summary

In this work package the development of word stress processing was investigated. Here we aimed at studying the early stages of word level stress processing in the first year of life. Our basic assumption was that only an integrative developmental model was able to account for differences found in the behavioural studies and the effect of intrauterine experience (and the possible causes of the shortening of the gestational period) might explain some crucial variations seen in this sensitive period. We assumed that the only rule used in Hungarian for word stress assignment might act as bootstrapping in perceiving the language-specific suprasegmental features. We also assumed an ongoing interaction with the segmental features contributing to the early lexical development. Our goal was to design new experimental paradigms helping to shed light on both the maturation and the development via investigating the emerging early language processing. We assumed that lexicality acted as a filter and facilitated the processing of familiar stress cues.

In order to answer our research questions event related brain potentials (ERPs) were measured as sensitive correlates of auditory feature or rule contrasts used in different paradigms. Here we took advantage of the indirect measure of neural representation, the infant equivalent of Mismatch Negativity called Mismatch Response (MMR) obtained in a passive oddball paradigm. Furthermore, we also designed a behavioural experiment using head-turn preference

paradigm (HPP) to be able to integrate our results into those of the most important studies of the field. The main idea of this series of experiments was to investigate 1) different age groups (groups from the sensitive period and matured participants); 2) with the same sets of stimuli; 3) with different techniques (ERPs) head-turn preference paradigm=HPP).

- Our first results in this projects revealed that even 6-month-old infants were sensitive to both types of cues and this was valid for words as well
- Our findings on brain responses specific to the predominant stress pattern in infants strengthen the view that complex language-specific templates emerge during infancy and this is as early as the 6th month of age.
- Our data provided electrophysiological evidence on the early interaction of suprasegmental and lexical processing on the proto-lexical level. Infants' linguistic processing showed quantitative and qualitative differences as compared to adults. Our newest data showed a general enhancement of familiar word form on stress processing.

Experiment 1a ERP experiment with infants: pseudo-words

- With this experiments we aimed at investigating the development of word application of stress assignment rules in infants in order to understand how sensitive Hungarian infants in acquisition of a fixed stressed language are to pattern changes, and how this processing differed from that of adults. For this we used phonotactically correct nonsense words (e.g. pseudo-words) of legal and illegal stress delivered in passive oddball blocks and investigated the mismatch response (MMR) elicited. We made use of the fact that all spoken language attributes were influenced by long term representations for segmental (Näätänen et al., 2007) as well as for suprasegmental cues (Honbolygó & Csépe, 2013).
- Our first results in this project revealed that even 6-month-old infants were sensitive to both types of cues and this was valid for words as well (Ragó et al., 2013).
- Our findings on brain responses specific to the predominant stress pattern in infants strengthen the view that complex language-specific templates emerge during infancy and this is as early as the 6th month of age.
- Status:
- Paper published
- Ragó, A., Honbolygó, F., Róna, Z., Beke, A., Csépe, V., 2013. Effect of maturation on suprasegmental speech processing in full- and preterm infants : a mismatch negativity study. Research in Developmental Disabilities 35, 192–202.
- Manuscript resubmitted after revision (under editorial decision)
- Garami, L. Ragó, A., Honbolygó, F., Csépe V. Brain responses to word stress violation modulated by proto-lexical speech processing. *Developmental Cognitive Neuroscience*

Experiment 1b. HPP experiment with infants: pseudo-words

- In this sets of experiment, we were interested in how behavioral and electrophysiological data correlate. We conducted a HPP paradigm with 6 and 10 months old Hungarian infants. The experiment used the same set of stimuli as our earlier ERP paradigm that revealed discrimination abilities for illegal stress pattern in both 6 and 10-month-old infants without any age effect.
- Earlier behavioral as well as electrophysiological results support the presence of language-specific discrimination abilities in case of infants who are learning syllable-timed language with fixed stress pattern. However, the behavioral experiments failed to reveal any preference in a HPP without familiarization to one of the stress patterns in case of French infants at the age of 6 months. When using a discriminative HPP infants are familiarized to one kind of stimulus, and in the test phase, they discriminate the stimuli with the

familiarized feature from those that differ. When prior knowledge. If there is a difference in knowledge related to the presented stimuli, the lengths of habituation will not be identical as manifested in different looking or listening time. This listening preference was only shown for languages with contrastive stress pattern. Taking ERP results into account, it is surprising that although neural representations of native and nonnative stress pattern are already different at the age of 4 and 6 months even in fixed-stress languages as French and Hungarian, preference is not observed in behavioral studies. Here we have conducted a HPP experiment with the same stimuli as were used in an ERP paradigm. For the legally stressed pseudo-word "*bebe*", Hungarian infants showed discrimination abilities both at the age of 6 and 10 months in ERP paradigm. Based on the previous behavioral results, it would be plausible to assume that Hungarian infants' stress processing would be similar to those of French infants, who also acquire a fixed-stress and syllable-based language. At the age of 6 months, French infants showed discrimination abilities for stress patterns in a HPP paradigm with training phase using different tokens of a segmentally invariant set of stimuli. According to the results, the easier the discrimination, the more probable any preference appears. For this we used the same tokens of a single pseudo-word stressed legally or illegally. The mismatch between processing the two kinds of stress patterns is known to trigger different responses on neuronal level relying on long-term stress representation of the mother tongue.

- We found that 6-month-old infants do not show any preference for either legal or illegal stimuli. On the other hand, 10-month-olds showed novelty preference, as average looking time was longer for the illegal stress pattern.
- Our study is the first one to show expressed preference based on language experience of infants in acquisition of a language with fixed-stress pattern.
- Our results on 10-month-old infants revealed an expressed preference for illegal stress patterns, implicating expectancies for native language stress assignment.
- Status:
- Manuscript resubmitted, under review:
- Garami, L. Ragó, A., Honbolygó, F., Csépe V. Brain responses to word stress violation modulated by proto-lexical speech processing (HPP data included). *Developmental Cognitive Neuroscience*

Experiment 1c. ERP experiment with preterm infants: pseudo-words

- According to the original research plan, we have collected data for Exp 1c investigating the preterm infants' word stress template processing with the upper mentioned pseudo-words as stimuli in the same set as Exp 1a. To reach our aim precisely, namely to discriminate the effect of maturation and learning on language acquisition, we have broadened the age groups of the participants (extended research plan). Apart from 6 and 10 months old infants we invited 2 more age groups: corrected age of 6 and 10 months.
- Finally, following the original research plan we have completed the measurement with all the age groups. We investigated sixty infants in total (14 non-corrected 6 month-olds, 17 corrected 6 month-olds, 16 1 non-corrected 10 month-olds, and 13 corrected 10 month-olds).
- Status:
- Manuscript resubmitted, under review:
- Garami, L. Ragó, A., Honbolygó, F., Csépe V. Brain responses to word stress violation modulated by proto-lexical speech processing (word, pseudo-word and HPP data included). *Developmental Cognitive Neuroscience*
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Experiment 2a. ERP experiment with infants: words

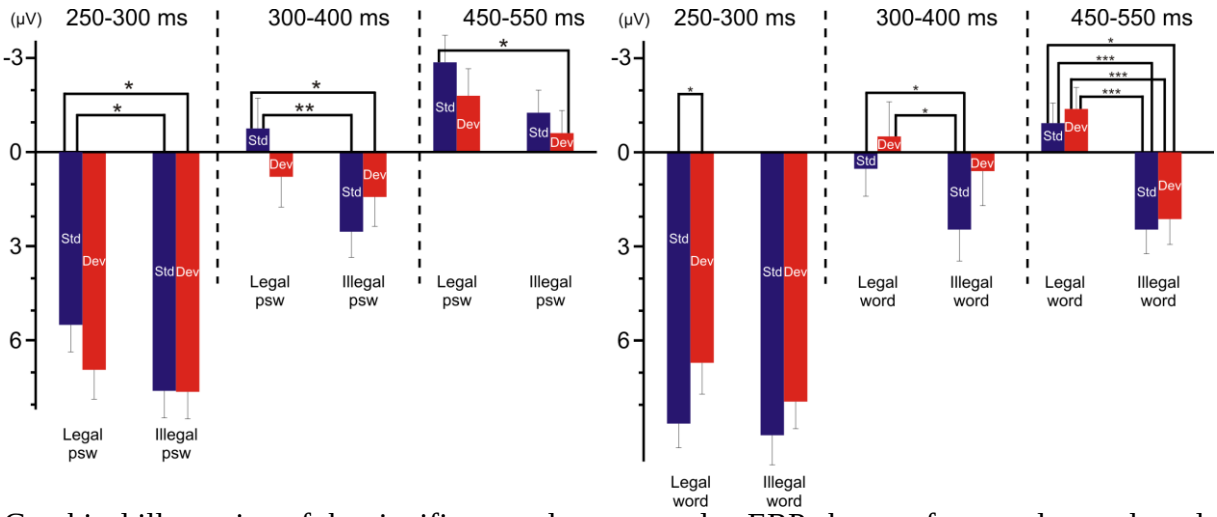
To overcome the problem of building a vocabulary out of nothing infants rely on prelexical cues to segment fluent spee. When infants were tested with single cues, phonotactic regularities, allophonic variations of phonemes, and prosody of native language were all have been shown to be useful markers of segmentation as shown by the classical studies (Jusczyk et al., 1999). However, data are controversial when more than one cues are taken into account. Experiments using different type of cues collided, are assessing the competing nature of the available linguistic cues, and could not explain how the identification of these regularities is taking place. The focus of recent theories has shifted towards the interplay of the different cues. There is evidence for word-level information shaping fine-grained phonetic categories (Swingley, 2009), parallel acquisition of speech sounds and word categories are in a potential interaction (Feldman et al., 2013) and proto-lexicon infers with allophonic variation increasing performance (Martin et al., 2013). (Proto-lexicon is a preliminary collection of potential word forms based on frequency distribution that temporarily contains both words and pseudo-words before building a lexicon that links meaning to the valid labels only (Ngon et al., 2013). We we -lexical access on prosodic processing. We aimed at showing how word familiarity influences the processing of word stress. For that we manipulated the word-level stress in both words and pseudo-words. As Hungarian is a fixed-stress language with the sole rule that stress is always on the initial syllable, we applied both legally (according to the rule) and illegally (against to the rule) stressed versions of the word. From the (proto)lexical level we picked a highly frequent Hungarian word “baba” (“baby”) for stimulus in our experiment to ensure the familiarity of the word form already for 6-month-old infants. Our main objective was to investigate the specific level of this discrimination bias, as well as the extent of familiarity effect on the MMR to prosodic information. As our study revealed:

- The illegally stressed stimulus as a deviant elicited a mismatch response (MMR) after the second syllable. This indicated that infants at this early age can successfully discriminate the illegal stress pattern in case of pseudo-words and words as well.
- Discrimination of the legal stress pattern elicited significant responses only for words. Legal word as deviant was accompanied by two mismatch responses (MMR) both synchronized to the onset of the syllables.
- Based on the comparisons of pseudo-word and word stimuli we concluded that the emerging proto-lexicon and the representation of stress assignment under development interact when infants listen to isolated words of violated stress.
- Although our data speak for an increasing impact of familiar word form on processing word stress, it differs from that observed in adults. The familiarity of word forms further strengthens the emerging long-term templates derived via rule extraction in form of an abstract regularity provided by the fixed stress word-level pattern.
- The MMR changes found revealed very flexible processing of word stress when (proto)lexical information was available. For this is a rather probable explanation that meaning takes the lead and wins the competition between two representations, e.g. meaning and stress assignment under development.

Status:

Manuscript resubmitted (under editorial decision):

- Garami, L. Ragó, A., Honbolygó, F., Csépe V. Brain responses to word stress violation modulated by proto-lexical speech processing (word, pseudo-word and HPP data included). *Developmental Cognitive Neuroscience (see figure below)*



Graphical illustration of the significant and very complex ERP changes for pseudo-words and words in infants (frontal electrode sites).
* $p < .05$; ** $p < 0.01$; *** $p < 0.001$.

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Experiment 2b. ERP experiment with adults: words (*change of the original research plan*)

- For understanding the developmental pattern found we conducted an additional ERP experiment with adults. Besides of this reason, this experiment is unique in itself as we tested the lexicality effect in a fixed-stressed language as Hungarian (no study known for fixed-stress).
- Our study was designed to overcome with the limitations of two earlier studies by applying specific conditions. Ylinen and her colleagues (2009) used only legally stressed pseudo-words as standards and observed delayed MMN responses for word deviants with illegal stress pattern, so that dividing the lexical and prosodic levels of processing is ambiguous (Ylinen, Strelnikov, Huotilainen, & Näätänen, 2009). Honbolygó and Csépe (2013) used only pseudo-words of different stress patterns (legal and illegal) and suggested a template-based processing for prosody for meaningless, phonotactically legal stimuli. Therefore, the main objective of the additional study was to shed light on the effect of prosodic information in the presence of lexical access in a fixed-stress language. Our other studies in this project provided solid evidence for assuming that the ongoing processing of complex stress patterns did not solely rely on comparing the salient acoustic features.
- Again, we tested words with legal and illegal stress patterns using them both in standard and in deviant roles across conditions. Our aim was to examine whether the illegal stress pattern delays the MMN when it plays a deviant role as it did in the Ylinen et al study (2009) and whether the template-based processing takes place at all when lexical information is easily accessed.
- We have conducted a passive oddball ERP experiment, presenting a frequent CVCV word with legal (familiar) and illegal (unfamiliar) stress patterns in a fixed-stress language. Hungarian adults responded with one MMN to the illegally stressed words as it was obtained for the illegally stressed pseudo-words (Honbolygó & Csépe, 2013) synchronized to the second syllable. It could reflect the additional stress on this syllable, or the reversed stress pattern as a genuine unit. As our results showed:
- When illegal stress patterns were contrasted with legal ones, the familiar patterned deviant word elicited two consecutive MMN responses. Pseudo-word deviants of legal stress did not elicit any MMN. The MMNs were synchronized to the syllables with additional stress

and lack of stress for word only. In this condition lexicality clearly enhanced the comparison of prosodic information between standard and deviant stimuli, contrary to the other condition.

- Lexicality or segmentation cues acted as different filters. In the absence of segmentation familiarity, unfamiliar stress patterns were discriminated better. In the presence of segmentation familiarity other cues indicating the perfect match with lexically rich representations are exploited.

Status:

Revised manuscript submitted:

- Garami, L. Ragó, A., Honbolygó, F., Csépe V. Lexical influence on stress processing in fixed-stress language. *International Journal of Psychophysiology*

Results of work package 2 were included in the PhD dissertation of Linda Garami defended in 2015. Linda Garami, a postdoc at Baycrest College in Toronto, works further in collaboration with our group on the infant studies continued by a doctoral student of the PI.

Cues and templates in reading
Work package 3[1]
Investigating orthographic processes in developing/skilled readers

Short summary

In a large-scale developmental study (N>250) we showed that the letter transposition effect is not an inherent consequence of visual processing but reflects an adaptive, letter-string-specific response of the orthographic system. Furthermore, in EEG studies we found that automatic processing of strings of familiar letters develops already in first grade and the emergence of this specific brain response cannot be explained by pure visual learning mechanisms.

Experiment 1 Development of orthographic processing (behavioural study)

Reading is an acquired skill; both of its core components, phonological decoding and especially orthographic processing take years of intensive practice to master. Despite the inherently developmental nature of orthographic processing, surprisingly few experimental data are available about the development and specificity of its basic processes: character identity and position encoding in letter strings. This is somewhat unexpected given the remarkable interest in the very same processes in skilled reading, especially in computational modeling.

How to represent letters and their positions emerged as a central question for recent computational models of visual word recognition. Indeed, these models excel at explaining various phenomena of base-level orthographic processing – most notably the so-called transposed-letter (TL). The TL effect refers to the finding that adult readers can be strikingly insensitive to the position of internal letters compared to their sensitivity to the identity of the same letters. Whether the transposition effect is *selective* (specific to letter strings) and *adaptive* (helps to achieve better word recognition performance) is still unclear. That was the focus of the present experiment.

A large, cross-sectional sample of more than 200 children from grade 2 to grade 4 was exposed to pairs of words, pseudo-words, digit strings, and pseudo-letter (Armenian) strings while their sensitivity to transpositions (T) and substitutions (S) of internal characters was investigated in a perceptual matching task. Our hypothesis was simple: if the transposition effect is selective, it should be substantially larger for pseudowords or words compared to digit or Armenian letter strings (note that Hungarian readers are not familiar with Armenian letters). Furthermore, if the transposition effect is adaptive, it should increase as children progress in the school or as their reading skill increases.

[1] *Work package 3 was based on the foundational work of Dénes Tóth included in his PhD dissertation defended in 2012.*

The main findings can be summarized as follows: 1) character identity encoding was much more efficient for digits and letters compared to pseudo-letters, and this sensitivity gradually and independently increased with reading ability and exposure to formal education; 2) position encoding in digit strings was almost as efficient as identity encoding and showed the same relationship with reading ability and exposure to formal education; 3) position encoding in letter strings (i.e., pseudowords and words) did not depend on subject-level factors, resembling the poor sensitivity of pseudo-letter processing. The results were successfully reproduced in two small independent samples of grade 3 children (N=25) and adolescent students (N=19). As our results show:

- The pattern of results indicates that the transposition effect is highly specific to letter strings because its development and its relationship with reading ability qualitatively differ from the processing of other familiar character strings, like digit strings. It is also clear that the transposition effect is not a limitation but reflects successful adaptation to the demands of fast and efficient letter-string processing: More talented readers or those with longer exposure to formal education showed larger TL effect in our task. To summarize, the transposition effect is both selective and adaptive.
- We proposed a general framework, the Adaptive Specialization Hypothesis to accommodate the results. According to this hypothesis, the transposed-letter effect is not a hard-wired feature of the orthographic processing system but an adaptive response of the developing orthographic system to the constraints of lexical access in several orthographies.

Status:

Publikáció:

- Tóth, D. and Csépe, V. (2017) Adaptive specialization in position encoding while learning to read. Developmental Science (published online in May 2016)

Experiment 2 Development of orthographic processing (electrophysiological study)

In the original project plan, Experiment 2 was designed as a developmental ERP study on 60 school children and 20 adult skilled readers focusing on orthographic processing. However, after finalizing the experimental paradigm (a novel implicit reading task, see later) we decided to split this experiment into two parts: in Experiment 2a only adults would be included because a previuosly untested experimental paradigm would probably lead to low signal-to-noise ratio, high attrition rate, and low data quality in general if conducted on young children. In Experiment 2b, including young school children in grade 1 and grade 3, we would use a simplified paradigm focusing on the most important effects.

Experiment 2a Adult skilled and dyslexic readers

In this experiment we investigated group differences between adult skilled and dyslexic readers in the N170 effect, an electrophysiological marker of visual expertise for processing letter strings, and N300, a component related to orthographic-phonological mapping. Developmental dyslexia is a neurodevelopmental disorder which primarily manifests in slow and inaccurate visual word recognition, spelling, and phonological decoding. Although not present in the

original plan, the inclusion of dyslexic readers helped us disentangle the developmental effects from the effect of reading level. This decision was also motivated by the expectation that the well documented phonological impairment of dyslexic readers could help reveal the role of phonological processing in seemingly orthographic-driven processes.

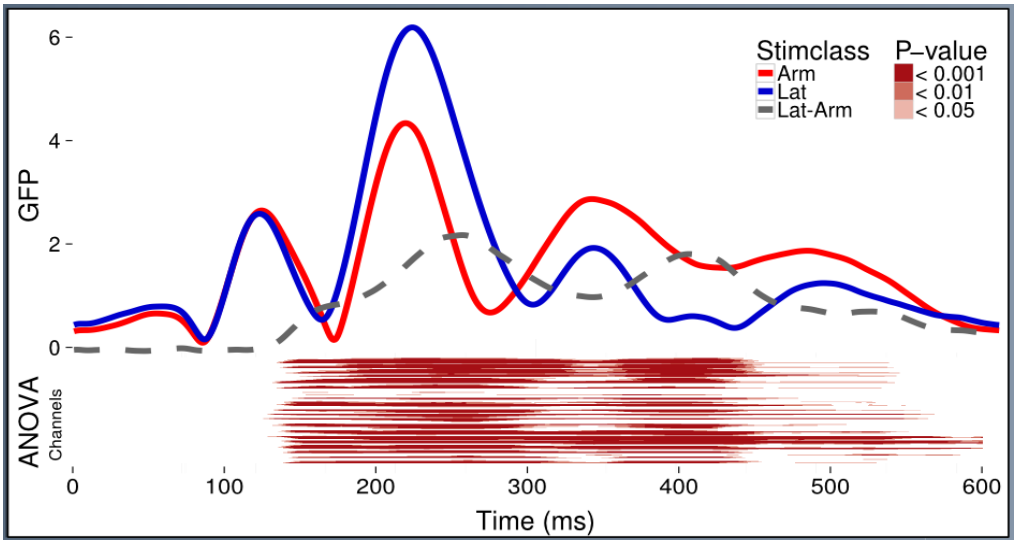
Fluent reading is enabled by the fast and automatic processing of orthographic stimuli (letter strings). The process that is thought to underlie this automatic visual word recognition is the visual specialization for letter over symbol strings. According to electrophysiological research, the electrophysiological marker of this form of visual expertise is the left-lateralized N170 component. The N170 has a characteristic scalp topography with positive distribution over the anterior and negative distribution over the posterior sites. Several previous studies showed that orthographic stimuli consistently elicit larger responses compared to control stimuli such as symbol strings, especially over the left posterior-occipital regions, referred to as N170 effect.

In the present experiment we focused on two main research questions: 1) How specific is the N170 component, that is, is it sensitive to subtle orthographic differences (character transpositions and substitutions) within stimulus classes, and is it sensitive to the status of a familiar character (letter versus digit strings) and the lexical status of the item (words versus pseudowords)? 2) Is the N170 attenuated in dyslexic readers? If yes, is the impairment more pronounced if it requires automatic grapheme-phoneme mapping?

To shed light on the above questions, we developed a novel implicit same-different paradigm which measures automatic orthographic processing. The development of a novel paradigm was motivated by the fact that in the generally used experimental setup – in the so-called one-back task – strategic and memory factors can bias the automatic orthographic processes. In our paradigm, the participants had a very simple task: to push a button if a bold-faced stimulus is presented on the screen. 3-5 character long Armenian letter strings (Armenian is an unknown alphabet to Hungarian readers), digit strings, pseu-words, and words were displayed in separate blocks. In each block and in each trial, a reference stimulus was presented first and followed by a target stimulus which could be identical to the reference (e.g., ÖKÖR-*ÖKÖR* [ox]), or a transposed (ÖKÖR-*ÖRÖK*) or one-character substituted (ÖKÖR-*ÖKÖL*) pair of it. In 10% of the trials, the target stimulus was written in bold-face and thus required an overt response (button press) from the participant. These item pairs served as filler trials and were not included in the ERP analysis. This visual-only (V) experimental setup was extended by an audiovisual (AV) setting in which the visual target stimuli was presented alongside its auditory pair. In the AV condition, only pseudowords and words were included. The explicit task of the participant did not require any orthographic or phonological processing per se. However, because the N170 effect was claimed to reflect *automatic* orthographic processes, we expected strong N170 effect for both the reference and target stimuli. We also hypothesized that the N170 would be sensitive to more subtle orthographic differences, that is, to transpositions or substitutions if the stimulus is a string of familiar characters.

Altogether sixty participants (27 dyslexics) were tested in the experiment. EEG data were collected using a 32-channel EEG system (BrainAmp, BrainProducts GmbH). Besides the EEG measurement, all participants performed a series of behavioural subtests of the 3DM-H dyslexia battery (phonological decoding fluency, phonological awareness, rapid automatized naming,

Corsi block tapping task) and three further tasks measuring reading fluency (sentence verification and proofreading task) and orthographic knowledge. Based on the behavioural screening tests and the results of EEG preprocessing, we selected 23 dyslexic and 26 control readers for further analysis. We performed two series of stimulus-locked ERP analyses. All analyses were carried out in the open-source R statistical programming language, using a custom R package (see later).



The N170 effect in 1st graders showing an exclusive sensitivity to the familiar print (blue curve (manuscript in preparation)

- We found a very strong N170 effect, thus, we successfully replicated the previous findings in a novel paradigm: the processing of strings consisiting of familiar characters (digits or letters) did differ from the processing of Armenian strings. Somewhat unexpectedly, the N170 effect did not differ between digit and letter strings. Although dyslexic readers produced weaker N170 effect in average, this difference was not significant.
- In the V condition we found strong main effects of stimulus class (starting well before the N170 time window), of pair type (starting at the early portion of the N170 time window), and of reading group (starting in the N170 time window). Surprisingly, we did not detect any interaction between the above factors except for a late (>300 ms) difference between identical and different pairs only
- The main effects found in the AV conditions as factors (stimulus class, pair type, reading group) were significant, such as the interaction between stimulus class and reading group. The interaction was in full accordance with our hypothesis: participants in the control group showed stronger N170 effect than dyslexic readers.
- In summary, our results supported the view that the N170 effect reflects automatic orthographic processing which might form the basis of both fine-grained and course-grained word recognition and naming. Furthermore, the N170 effect – the visual expertise or increased sensitivity to digit and letter strings – might be attenuated in dyslexia, probably caused by impaired grapheme-phoneme mapping.

Status:

Publication

- Csépe, V. (2014) Az olvasás zavarai és a diszlexia. In Pléh Csaba és Lukács Ágnes (szerk), Pszicholingvisztika, Akadémiai Kiadó, Budapest, 1326-1344.

Manuscript in preparation to be submitted by the end of February

- Tóth Dénes, Varga Vera, Csépe: The non-trivial emergence of visual expertise for print. (presented: MPT, 2015, COST ELN, 2016, 2017)

Experiment 2b Automatic letter-string specific processing in beginner and developing reader

In the follow-up experiment of Experiment 2a, we used a simplified and partly modified version of the implicit same-different paradigm to test automatic letter-string specific processing in beginner and developing readers. We aimed at answering three research questions: (1) Does the N170 effect emerge as early as grade 1? (2) Does it undergo further development by grade 3? (3) Is its development driven by grapheme-phoneme mappings?

The following major modifications were introduced compared to Experiment 2a:

1. We reduced the stimulus set to two stimulus classes: Armenian strings and pseudo-words; to two pair types: identical or one-letter substituted; and to two stimulus lengths: 3-character or 5-character strings. Thereby we substantially reduced the net EEG measurement time, which was necessary to keep the children motivated during the experiment. Additionally, we gave audiovisual feedback after each filler (bold-faced) item or in case of false arams (e.g., "Well done!" appeared on the screen and the Windows "Tadaa" sound was played if the child responded correctly).
2. In the AV condition, we presented visually both Armenian and pseudoword strings, together with an auditorily exposed pseud-oword. Thereby the AV condition was fully identical to the V condition except for the parallel auditory stimulus. Furthermore, because Armenian letters can not activate phonological representations, they served as a perfect control to test whether beginner readers would automatically perform grapheme-phoneme mapping of pseudowords in the AV condition.
3. The EEG data were recorded with a 128-channel HydroCel Geodesic Sensor Net (GES 300, Electrical Geodesic Inc., Eugene, OR, Net Station software), amplified by an EGI Net Amp 400 (Electrical Geodesic Inc., Eugene, OR) amplifier. Dense electrode nets are more favorable if whole-scalp scalp analytic methods are applied.

Thirty-two children in Grade 1 and 28 in Grade 3 participated in the experiment which was carried out in April (the eighth month of reading instruction in Grade 1). After data preprocessing, the final sample consisted of 24 first graders and 17 third graders. The older group performed much better in all selected subtests of the 3DM-H reading battery (reading fluency, spelling accuracy, phoneme deletion, rapid automatized naming, letter-sound correspondence, choice reaction time).

- In accordance with our hypothesis, we found highly significant N170 effect even in beginner readers: although the task did not require any orthographic processing per se, school children after a couple of months of reading instruction processed the pseudowords as orthographic stimuli.

- Surprisingly, the N170 effect found in Grade 1 was not only left-lateralized, but its intensity and scalp distribution did not significantly differ from the those found in Grade 3. This result might suggest that sensitivity to letter strings – a basis of both visual word recognition and phonological decoding – reaches its maturity by the end of Grade 1 in most children. Moreover, this is not a simple form of visual expertise (which would result in right-lateralized N170 effect), but is related to language processing as seen in adult readers.
- We suggest the N170 effect found in beginner readers as the result of a very fast tuning of the orthographic system. However, as it seems, a further refinement needs several years of reading experience.
- Regarding our third hypothesis, we expected stronger N170 effect in the AV condition than in the V condition (note that this analysis was only relevant for target stimuli). The result exactly confirmed our hypothesis. Thus, the N170 effect was not only left-lateralized, which might be an indirect evidence for its link to language and especially grapheme-phoneme mapping, but it was also modulated (enhanced) by a task irrelevant auditory stimulus. Taken together, our results suggest that the N170 effect is not a pure visual learning effect.

Status:

Manuscript in preparation (to be submitted in February and March)

- Dénes Tóth, Vera Varga and Dénes Tóth:Automatic letter-string specific processing in beginner and developing reader (presented at BACN 2016)

In both EEG experiment, we used our (developed by Dénes Tóth) custom R package (eegR) to analyze the ERPs. Since R is a free and open-source programming language (in contrast to e.g. MATLAB, a popular choice in the field of cognitive neuroscience), our package (which is publicly available on www.github.com/tdeenes/eegR) can help those who do not have access to commercial analytic softwares. In addition, we implemented several modern ERP analytic methods in this package (e.g., point-by-point ANOVA with threshold-free cluster enhancement) and several convenience functions for plotting and summarizing the results.

Status:

Publication

- Dénes Tóth: eegR at www.github.com/tdeenes/eegR
  (first oral presentation in 2014, release version under development)

Experiment 3 Methodological aspects (extended study)

Besides the theoretical aspects of orthographic development and specialties of letter identity and position encoding, we were also interested how methodological aspects can influence the experimental results. Our major concern was that the masked priming paradigm – which is widely used in orthographic experiments and specifically in transposed letter (TL) experiments as well – makes the result far less generalizable as it is usually treated in the literature.

We implemented various experimental settings which are frequently used in the literature, and compared the task-dependency of the TL effect (see Experiment 1) in a within-subject design (i.e. the same subjects participate in all experimental settings). This experiment was also expected to provide background information to choose or develop the appropriate experimental

procedure for the developmental and more theory-focused block of the project (especially for Experiment 2).

The following experimental paradigms were implemented: masked priming lexical decision task, masked priming same-different task, non-primed same-different task with short parallel exposure of items, proofreading (sentence-level) and sentence verification (control task). The main questions were the following (the formulation of the questions corresponds to our hypotheses): (1) Does TL effect emerge in all paradigms? (2) Are there differences between the sensitivity of the paradigms? (3) Do individual-level TL effects correlate between different paradigms?

Thirty-five university students participated in the extended pilot experiment. All hypotheses were confirmed except the stability of individual letter position effects across experimental settings.

- The TL effect was very robust at the group level, clearly detectable in all paradigms. Regarding the size of the effect, the non-primed same different task (the one used in Experiment 1) was the most sensitive task while the masked paradigms produced the weakest effects. However, at the level of individuals, the TL effect was very unstable (the intercorrelation of individual TL effects was below 0.3).
- The extremely low reliability of the TL effect at the individual level (despite its robustness at the group level) was an unexpected result which might have serious consequences on all studies in which the TL effect was used as a precursor of individual reading ability (including our own experiment, Exp 1.). To test this finding in a more powerful way, we tried to transform the experimental setup into an online, web-based experiment which would allow the measurement of several hundred readers. However, we decided to postpone this experiment because we did not possess the human and financial resources to implement the software.

Status:

Publication: in preparation, to be submitted by the end of March

Pilot results presented: undergraduate essay (Krisztina Peres, ELTE); web experiment preparation

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Circumstances influencing the project's realazation

The project aimed at investigating a rarely studied aspect of speech with behavioural and brain methods in adults as well as in infants. This needed reanalysing the previous data and developing new paradigms as well as new methods. The participants (students, doctoral students and postdocs) led to minor changes, although the training they needed costed extra time (see at the changes section).
The research group moved by the end of 2013 to the MTA's Research Centre of Natural Sciences and in February 2014 a new formation of research group was established, the Brain Imaging Centre. Extra activities were put into the infrastructural development (MRI laboratory, 2015), the reestablishment of the EEG laboratories as well as the introduction of new stimulus delivery (MR compatible visual and acoustic devices) as well as the further development on TMS and MR-compatible multichannel EEG systems (2015-2016). The MR measurements planned in the original project application were moved to the new centre and the measurements started after calibrating, paradigm developing and getting the necessary permissions including the ethical approval.
The fulfilment of original goals were possible due to the one year extension of the project.