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<td>Su, IF; Lau, DKY; Yan, N; Law, SP; Zhang, Z</td>
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Awareness of form-sound correspondence in Chinese children with dyslexia: Preliminary results from event-related potentials and time frequency analyses

I-Fan Su, Dustin K-Y. Lau, Nan Yan, Sam-Po Law
Division of Speech and Hearing Sciences
University of Hong Kong
Hong Kong SAR

Zhiguo Zhang
Department of Electrical and Electronic Engineering
University of Hong Kong
Hong Kong SAR

Abstract—Developmental dyslexia has usually been characterized as having difficulties learning grapheme–phoneme correspondence and applying the mappings. This study investigates form-sound awareness in Chinese reading-impaired children in terms of regularity, consistency and lexicality effects using event-related potentials (ERP) and time-frequency analysis (TFA). Preliminary data from two Cantonese-speaking male children, one with reading impairment (PR) and one with normal reading performance (CA), performing a character recognition task were collected. ERP results indicated that CA showed a lexicality effect at N400 that was not evident in PR. TFA showed that CA exhibited greater event-related synchronization (ERS) and phase coherence at theta and gamma bands suggesting greater cognitive demand in processing pseudo and irregular characters. An opposite pattern was observed for PR, where greater effort was needed to retrieve information related to real and regular characters whilst failing to respond to pseudo and irregular characters. Greater ERS and phase coherence was also observed for real, pseudo and regular characters at 350-450ms at theta suggesting adequate access to phonological and semantic information for CA compared to PR. Whereas PR showed greater ERS and phase coherence at earlier and later time intervals. These initial findings suggest that PR may have weaker semantic representations and may be less sensitive to the internal structure of characters and its relationship with sounds.

Keywords—Chinese developmental dyslexia, awareness of form-sound mapping, event-related potentials, time frequency analysis, Chinese character recognition, phonological regularity, phonological consistency

I. INTRODUCTION

This Developmental dyslexia specifically affects children’s ability to learn sound-symbol correspondence and apply the mappings, which are critical in reading development, despite their normal intelligence and sensory abilities, and adequate learning opportunities. Individuals with developmental dyslexia are shown to have longer response latencies than normal readers in acoustic/phonological processing [1], and in rapid visual processing tasks [2]. Chinese children with reading disorders have also been found to show poorer performance than chronological age matched (CA) children with normal reading abilities on visual and auditory temporal processing tasks, and a correlation between reading performance and orthographic processing [3, 4, 5, 6, 7]. Differences at the brain level between dyslexic and normal young readers have also been found in neuroimaging studies employing functional magnetic resonance imaging (fMRI). In performing phonological judgment tasks, Chinese dyslexic children show greater activation compared with CA controls in the right inferior occipital cortex, which is associated with visual analysis of characters [8]. Furthermore, differing from similar studies of alphabetic scripts where activation in the left posterior temporoparietal region linked to grapheme-phoneme conversion is commonly involved [9, for a review], Siok et al. have found that Chinese subjects show activity in the left medial frontal gyrus (BA9) hypothesized to be related to integration of visual, orthographic, and semantic information, and that grey matter volume and level of activation in this region are significantly correlated with reading performance in children with dyslexia and CA controls. Farmer and Klein [10], among others, hypothesized that developmental dyslexia is strongly linked to a general deficit in speed of processing (SOP) in both visual and auditory modalities, and that SOP asynchrony between the two input modalities is an underlying factor for developmental dyslexia [11], as a prolonged mismatch between auditory and visual information processing speed may have cascading effects on subsequent higher level language/cognitive processes.

Given the hypotheses of speed of processing deficits and asynchrony between input modalities of developmental dyslexia, event-related potential paradigms (ERP) would be uniquely suitable for investigating the disorder [9]. ERP studies in the last decade have found deviant patterns in terms of reduced amplitude and/or longer latency of early (P2, N2) and late ERP (P300) components in dyslexic individuals participating in tasks of visual recognition of non-linguistic and linguistic stimuli of alphabetic scripts [1, for a review]. The mismatch negativity (MMN) has been used extensively to examine the sensitivity of individuals with dyslexia to various speech sound contrasts, including place of articulation, voicing, vowel and tone. Key findings of the relevant literature can be characterized by abnormal appearance of the MMN in terms of reduced amplitude or topographic distribution [12, for a review]. Compatible observations have recently been reported of Chinese children with dyslexia [13].
In this paper, we report preliminary behavioral and electroencephalogram (EEG) data from two Chinese young readers, a nine-year-old with developmental dyslexia and his age-matched control. Their awareness of form-sound mappings was measured in a lexical decision task with Chinese character stimuli varying in predictability of pronunciation from their sub-character components. In additional to behavioral measures in accuracy and response latency and traditional ERPs, brain activities were also analyzed using time frequency analysis (TFA), as amplitude changes in an ERP can arise from a change in power and/or phase-synchronization [14]. TFA with measures of event-related spectral perturbation (ERSP) and inter-trial coherence (ITC) would provide richer information on brain activities with respect to power modulation and oscillation across time windows and frequency bands including delta, theta, alpha, beta, and gamma, compared to averaged ERPs. Increasing evidence has suggested that these measures could reflect differences between normal and poor readers across frequency bands [15, 16, 17, 18]. The methodological significance of the present study, albeit preliminary, is that through employing single-trial and single subject analyses [14], we highlight an alternative approach which may be more appropriate for studying individuals with language disorders of possibly heterogeneous underlying causes. As different subtypes of developmental dyslexia have been proposed [19, 20], the single case approach can be considered a preferred investigative method for reading disorders in children.

II. METHOD

A. Participants

The participants were two age-matched right-handed Cantonese-speaking male students with normal non-verbal intelligence, one with reading impairment, PR and the other with normal reading performance, CA. PR (M / 9;06) just finished Grade 4 when he came to the dyslexia clinic in the Division of Speech and Hearing Sciences at the University of Hong Kong for treatment of his poor Chinese reading abilities. He had not received any treatment before. Pre-treatment assessment revealed a standard score of 113 in the Raven’s Standard Progressive Matrices (RSPM) [21], z-score of -1.43 in the Hong Kong Graded Character Naming Test (HKGCNT) [22], and z-score of -1 in the word reading subtest of the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT-SpLD) [23]. CA (M / 9;03) just finished Grade 3 at the time of the study. He obtained a standard score of 100 in the RSPM, z-score of 2.06 in the HKGCNT, and z-score of 2.00 in the word reading subtest of the HKT-SpLD.

B. Task and stimuli

A character recognition task was carried out in which they pressed separate buttons to indicate whether or not they had learned the character presented in each trial. Unlearned items were 160 pseudocharacters created by rearranging the radicals from real characters. Learned characters were those taught by Primary 2. The 160 real characters were selected in terms of number of strokes), and neighbourhood size (i.e. number of characters that can be derived from the given character by replacing one of the radical) were matched across the real word conditions, $F_{\text{frequency}}(3, 156) = 0.10, p > .05$; $F_{\text{complex}}(3, 156) = 1.24, p > .05$; $F_{\text{neighborhood}}(3, 156) = 1.47, p > .05$. Real and pseudocharacters were also matched for visual complexity, $t(304.8) = 1.02, p > .05$. Real: $M = 12.44 SD = 2.67$, Pseudo: $M = 12.01, SD = 3.29$.

C. Procedure

Yellow characters (100x90 pixels) were presented on a black background on the computer screen approximately 60cm away from the child using E-Prime software (Psychology Software Tools Inc., USA). The trial began with a fixation cross on the screen for 500ms followed by a blank screen of with a random duration of 300-500ms. A character was then presented on the screen until the child made a response. And a blank screen of 1000-1500ms was shown before the next trial began. Response latencies were measured from character onset, with a time-out point set at 3000 ms, i.e., responses given after 3000 ms were registered as missing. Each child was presented with a different random sequence of stimuli given in 6 blocks.

D. ERP data recording

The electroencephalogram (EEG) was recorded using SynAmps2 NeuroScan Inc. system in a sound attenuated and electrically shielded room with a 128 Ag/AgCl sintered electrode cap (Quik-cap, Compumedics Ltd., USA) arranged according to the Compumedics NSL system. The vertex served as the reference, and GND was located between channels 59 and 60. The vertical electro-ocularogram (VEOG) was monitored using electrodes placed above and below the left eye, and the horizontal EOG (HEOG) using two electrodes placed at the outer canthi of each eye. Electrode impedance was kept below 10 kΩ for all electrodes whenever possible. Data was sampled with a bandpass from 0.05 to 200 Hz and digitized at a rate of 1000 Hz.

E. Preprocessing parameters

ERP data was filtered offline using Neuroscan 4.5 software (Compumedics Ltd., USA) with a zero-phase shift bandpass 0.05 to 30 Hz with 12d/B slopes. Channels affected by eyblinks and horizontal eye movements were reduced using the ocular artifact reduction procedure. Epochs of -200ms pre-stimulus onset to 1000 ms post-stimulus onset were extracted. Trials with time-outs, errors and artifacts that exceeded ± 100 μV in any channel were excluded from the data analysis. Each channel was then baseline corrected using the -200ms prestimulus onset, re-referenced to an average reference, and downscaled to 250Hz for statistical quantification.

In the TFA, a zero-phase shift bandpass 0.05 to 100 Hz with 12d/B slopes was used. Correct trials were epoched at -500ms pre-stimulus onset to 1000 ms post-stimulus onset. Using EEGLAB [24], the data was downscaled to 250Hz, and subsequently noisy channels, muscle activity, and channels affected by eyblinks and horizontal eye movements were removed using PCA with 20 components to retain as many trials as possible. Trials with artifacts that exceeded ± 100 μV, trends greater than 75 μV, with abnormal distributions or...
improbable data exceeding 5 standard deviations in any channel were automatically rejected. Each channel was then baseline corrected (-500ms pre-stimuli onset), and re-referenced (average reference).

F. Data analysis

- Conventional ERP analysis – Bootstrap analysis with 1,000 permutations at each sample point was used to identify significant differences between real and pseudo characters for the lexicality effect at electrode 60 during the N400 time window, between regular and irregular characters for the regularity effect and between consistent and inconsistent characters for the consistency effect during the P200 time window at electrode 34. As consecutive time points are not independent of each other, the likelihood of obtaining spurious effects was corrected using false discovery rate (FDR) across the epoch.

- Single trial time-frequency analysis – EEGLAB software was used to run the TFA to obtain measures of ERSP and ITC. For these analyses, spectral power was measured at different time points in time during an epoch using fast-Fourier transform (FFT) and Hanning windows. The frequency range was specified at 1-50Hz, with a pad ratio of 8. To assess significant differences between conditions for these indices, bootstrap analysis with 10,000 permutations and FDR correction was used at each time point across conditions and across participants.

III. RESULTS

A. Behavioral data (response latency and accuracy)

Table 2 shows that CA was in general faster and more accurate than PR in making lexicality judgments regardless of the characteristics of the stimulus.

B. ERPs

As there were no observable effects of consistency, only effects of lexicality and regularity are reported. Fig. 1 shows that the bootstrap analysis revealed a significant difference during 400-500 ms post-stimulus (associated with N400 at electrode 60 or FCz) and a later time window (600 ms) for CA only (see Figure 1). Pseudocharacters elicited greater negativity than real characters. An observable greater positivity for irregular characters around 200 ms (P200) was found in CA at electrode 34 (F3), although the difference between regular and irregular characters failed to reach significance. Little difference was seen for PR.

C. TFA

Similar to ERPs, results are reported only for the lexicality and regularity contrasts. We focus on the theta band and gamma band since the former has been found to be sensitive to various language processes including perception of acoustic/auditory stimuli [25], lexicality [26], form class effects [27], syntactic violations [28], syntactically complexity [29] and semantic violation [30], and the latter reflects synchronization of activity at the cortical networks level [31].

Fig. 2 illustrates that CA exhibited greater event-related synchronization (ERS) around 500ms post-stimulus in gamma band and greater phase synchronization in theta band during 80-150ms for pseudo characters than real characters. In contrast, PR showed greater ERS in gamma band for an extended period post-stimulus for real characters and little change in phase synchronization. With respect to regularity (see Fig. 3), CA demonstrated greater ERS for irregular than regular characters after 650ms post-stimulus in theta band and throughout the time window post-stimulus in gamma band. Phase synchronization revealed an interesting pattern. Greater coherence across trials was found in CA for irregular characters in theta band after 500ms. While this difference in direction between conditions was seen in gamma band during 80-120ms and 450-600ms, the reverse was seen during 350-450ms and 580-700ms. For PR, greater ERS was observed very early on (around 100ms) for regular characters in gamma band, but followed by greater ERS for irregular characters during 150-250ms in the theta band. Greater phase synchronization was also found for irregular characters in the theta band for about 50ms after 250ms post-stimulus.

When comparing CA and PR by each experimental condition, PR showed greater ERS than CA in gamma band for the entirety of post-stimulus period for real characters and regular characters, and for pseudo characters after 600ms in lower gamma (30 Hz). The opposite was observed with greater ERS in CA than PR for pseudo characters during 550-650ms in upper gamma (40Hz). In theta band, PR revealed greater ERS during 100-300ms for real characters and irregular characters, and additionally after 700ms for the former. The opposite pattern of greater ERS for CA than PR was observed during 350-450ms for real characters, pseudo characters, and regular characters, and additionally during 550-600ms for pseudo characters. With respect to phase coherence across trials, greater synchronization was found for PR in the early portion of the time window post-stimulus (<300ms) for all types of stimuli, and additionally during 600-700ms for real characters, while greater coherence was seen for CA during 350-350ms for real characters and for 50ms after 530ms post-stimulus for pseudo characters. In gamma band, there were differences between the participants only for real characters, where CA showed greater phase synchronization early (<200ms) and late (>650ms) but the opposite pattern of greater coherence across trials for PR was observed during 300-450ms.

IV. DISCUSSION

The ERP patterns revealed an effect of lexicality reflected in N400 in CA, but not PR. Although the difference between regular and irregular characters did not reach significance, a tendency of greater positivity of P200 was noted, again only in CA. The observation of irregular characters eliciting greater P200 was compatible with reports of phonologically inconsistent characters inducing greater positivity in the P200 time window [32]. These findings suggest that CA is sensitive to the difference between real and pseudo characters perhaps in terms of the familiarity of the orthographic form, and between
regular and irregular characters regarding form-sound relationship. Both are lacking in PR.

When brain activities are examined in terms of power modulation and oscillation across time and frequency, CA exhibited greater ERS and phase coherence at various temporal windows in theta and gamma bands for pseudo characters and irregular characters than real characters and regular characters, respectively. This trend was seen in PR in the regularity contrast in an early time window in theta band. Such observations can be taken to indicate greater cognitive demand in processing pseudo and irregular characters. Interestingly, PR also demonstrated greater gamma ERS for real characters for extended periods in the post-stimulus time window and for regular characters shortly after presentation of stimulus. Previous research has suggested that children with dyslexia failed to respond to pseudo words [26]. Seen in this light, we propose that PR may not be responsive to pseudo characters at the cortical systems level [33] and find it difficult to retrieve information related to real characters during recognition. We further suggest that an analogous account apply to processing regular vs. irregular characters. Another interesting observation of gamma phase synchronization in CA was two cycles of alternating pattern of greater coherence for irregular than regular characters followed by greater resetting for regular than irregular items over the post-stimulus time window. We believe that it is important to see if other normal young readers exhibit such a pattern before an explanation should be attempted.

A more exploratory comparison was one between the two participants. It showed generally greater event-related and phase synchronization for PR than CA across the post-stimulus time window, early on (<300ms), and relatively late (>600ms). Exceptions were CA exhibiting greater neural activities in theta band for real characters, pseudo characters, and regular characters around 350-450ms, and in gamma band early on (<200ms) for real characters, and late (>550ms) for both real and pseudo characters. While the differences during that temporal window in theta band can be interpreted as access to phonological and semantic information of the stimuli on the part of CA [27, 34, 35], the mechanism underlying the differences in gamma band is not clear.

The null effects of phonological consistency can be related to the relatively later emergence of sensitivity to consistency as such an effect requires the acquisition of characters sharing the same phonetic radicals and an awareness of form-sound relation across lexical items. It is probable that our participants are at a stage of literacy development that is too early to see the consistency effect reliably.

In summary, our preliminary investigation of deficits in awareness of form-sound correspondence, semantic access and possibly orthographic processing of characters in Chinese developmental dyslexia has revealed a range of interesting cognitive differences over the time course of character recognition between a Chinese poor reader and his age-matched control. These phenomena can only be captured by a technique with excellent time resolution. Our methodological approach has also highlighted the advantages of single-subject single-trial analyses to study a disorder that is likely to be heterogeneous in nature.

ACKNOWLEDGMENT

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### TABLE 1. CHARACTERISTICS OF STIMULI IN DIFFERENT EXPERIMENTAL CONDITIONS

<table>
<thead>
<tr>
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<th>RC</th>
<th>RIC</th>
<th>IRC</th>
<th>IRIC</th>
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<tbody>
<tr>
<td>M</td>
<td>11.63</td>
<td>11.80</td>
<td>12.90</td>
<td>12.38</td>
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<tr>
<td>SD</td>
<td>3.07</td>
<td>3.47</td>
<td>3.03</td>
<td>3.36</td>
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<td>Range</td>
<td>[6-20]</td>
<td>[5-21]</td>
<td>[8-20]</td>
<td>[7-20]</td>
</tr>
<tr>
<td>M</td>
<td>100.85</td>
<td>106.35</td>
<td>107.65</td>
<td>113.15</td>
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<tr>
<td>Frequency (Cumulative)</td>
<td>110.58</td>
<td>109.87</td>
<td>121.47</td>
<td>124.52</td>
</tr>
<tr>
<td>SD</td>
<td>8-491</td>
<td>7-502</td>
<td>6-469</td>
<td>6-554</td>
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<tr>
<td>Token Consistency</td>
<td>0.90</td>
<td>0.21</td>
<td>0.87</td>
<td>0.21</td>
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<td>Neighborhood Density</td>
<td>0.10</td>
<td>0.13</td>
<td>0.09</td>
<td>0.14</td>
</tr>
<tr>
<td>Range</td>
<td>[0.7-1]</td>
<td>[0.01-0.48]</td>
<td>[0.72-1]</td>
<td>[0.01-0.49]</td>
</tr>
<tr>
<td>M</td>
<td>194.65</td>
<td>144.95</td>
<td>165.60</td>
<td>151.03</td>
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<tr>
<td>Neighborhood Density</td>
<td>111.12</td>
<td>103.48</td>
<td>124.44</td>
<td>121.83</td>
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<tr>
<td>SD</td>
<td>8-372</td>
<td>7-375</td>
<td>13-372</td>
<td>13-377</td>
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<tr>
<td>Range</td>
<td>[8-372]</td>
<td>[7-375]</td>
<td>[13-372]</td>
<td>[13-377]</td>
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Note. RC=Regular Consistent, RIC=Regular Inconsistent, IRC=Irregular consistent, IRIC=Irregular Inconsistent

### TABLE 2. BEHAVIORAL PERFORMANCE IN PROPORTION CORRECT AND MEAN RT

<table>
<thead>
<tr>
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<th>CA</th>
<th>PR</th>
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<tr>
<td>Lexicality</td>
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<td></td>
</tr>
<tr>
<td>Real character</td>
<td>0.78 (852ms)</td>
<td>0.90 (599ms)</td>
</tr>
<tr>
<td>Pseudo character</td>
<td>0.58 (952ms)</td>
<td>0.91 (625ms)</td>
</tr>
<tr>
<td>Regularity</td>
<td></td>
<td></td>
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<tr>
<td>Regular</td>
<td>0.79 (843ms)</td>
<td>0.89 (601ms)</td>
</tr>
<tr>
<td>Irregular</td>
<td>0.78 (862ms)</td>
<td>0.91 (598ms)</td>
</tr>
<tr>
<td>Consistency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consistent</td>
<td>0.81 (836ms)</td>
<td>0.94 (613ms)</td>
</tr>
<tr>
<td>Inconsistent</td>
<td>0.75 (848ms)</td>
<td>0.86 (584ms)</td>
</tr>
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Figure 1. Mean ERP waveforms comparing effects of lexicality (FCZ) and regularity (F3).

Figure 2. ERSP and ITC of lexicality effects (FCZ) across frequency bands for CA and PR. (Significant differences with FDR correction between conditions encircled by black lines, and between participants by grey line)

Figure 3. ERSP and ITC of regularity effects (F3) across frequency bands for CA and PR. (Significant differences with FDR correction between conditions encircled by black lines, and between participants by grey line)