Selective attention and the “Asynchrony Theory” in native Hebrew-speaking adult dyslexics: Behavioral and ERPs measures

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Abstract. The main aim of the present study was to determine whether adult dyslexic readers demonstrate the “Asynchrony Theory” (Breznitz [143]) when selective attention is studied. Event-related potentials (ERPs) and behavioral parameters were collected from non-impaired readers group and dyslexic readers group performing alphabetic and nonalphabetic tasks. The dyslexic readers group was found to demonstrate asynchrony between the auditory and the visual modalities when it came to processing alphabetic stimuli. These findings were found both for behavioral and ERPs parameters. Unlike the dyslexic readers, the nonimpaired readers showed synchronized speed of processing in the auditory and the visual modalities while processing alphabetic stimuli. The current study suggests that established reading is dependent on a synchronization between the auditory and the visual modalities even when it comes to selective attention.

Keywords: Dyslexia, ERPs, selective attention, asynchrony

1. Introduction

Word recognition is a basic reading skill, thought to be a complex cognitive process involving the integration of information from several modalities (Van Atteveldt, Formisano, Goebel, & Blomert [58]). Although most of the population in literate countries read well, about 10% demonstrate reading difficulties despite adequate intelligence, education, and social background. These difficulties are attributed to developmental dyslexia, which is thought to be neurological in its origin (Ramus [42]). Dyslexic readers demonstrate deficits in word decoding (Adams [2]; Stanovich [53]), and the explanation for this deficit and its cognitive basis remains the subject of ongoing research.

Different researchers point to phonological deficits as a cognitive marker in developmental dyslexia (Lyon, Shaywitz, & Shaywitz [36]; Liberman & Shankweiler [35]; Ramus [42]; Stanovich [52]), while others emphasize orthographic deficits (Barker, Torgesen, & Wagner [6]; Cunningham & Stanovich [17]). Although both phonological and orthographic processing are required for word decoding, the way in which these parameters affect the process of decoding is still unclear. An influential connectionist model (Seidenberg [45]) of reading assumes the existence of parallel phonological and orthographic...
processes activating semantic representations of the written materials. Each of these systems is based on separate modalities which process the information at a different speed and in different manners. The phonological system operates via an auditory route, analyzing the phonemic information from printed words (Baddeley [4]). It is known that this type of information is processed in a sequential manner, while the orthographic system analyzes information about the visual stimuli comprising the words in a more holistic way (Rosenzweig & Bennett [44]). Hence, it can be argued that the analysis of words is faster through the visual than the auditory route.

Based on the connectionist model (Seidenberg [45]), it can also be argued that accurate word recognition requires the appropriate connections between graphemes and phonemes. In order to achieve an accurate grapheme-phoneme connection, stimuli must be coordinated at different stages of information processing. Accordingly, successful word decoding and reading require a synchronization between auditory and visual aspects of printed words for cognitive processing within a certain time frame.

Different studies focusing on fluency in reading have found that dyslexic readers in different ages decode words more slowly than nonimpaired readers (Ackerman & Dykman [1]; Badian [5]; Breznitz [9,10]; Denckla & Rudel [18]). Gough and Tunmer [28] argued that the slow decoding speed is an outcome of the impaired word recognition skills which characterize dyslexic readers. Furthermore, it has been found that dyslexics in different ages demonstrate a slow functioning of working memory (Breznitz [10]), slow word retrieval (Breznitz [8]), and slow naming speeds (Bowers & Wolf [7]). Thus, it can be argued that speed of word recognition may reflect a general deficit in the speed of processing (SOP).

The “asynchrony theory” (see Breznitz [12], for an overview) suggests that the SOP of the visual (orthographic) and the auditory (phonological) modalities operate at different speeds in dyslexic readers. For intact reading process, both systems must be integrated, or synchronized, at the perceptual level to formulate correct grapheme phoneme correspondence. According to this, dyslexic readers demonstrate word decoding difficulties because of their failure to synchronize between the SOP of the visual and the auditory modalities which results in a wide SOP gap between the two modalities. The SOP is thought to be a crucial cognitive marker when it comes to reading (Breznitz [12]).

This theory has been studied in children and adult dyslexic readers, via the use of behavioral and event-related potentials (ERPs) parameters. For example, in a study conducted in elementary school children, the SOP has been studied using both nonlinguistic and linguistic auditory and visual low-level tasks as well as higher-level orthographic and phonological tasks. It was found that dyslexic readers were significantly slower than nonimpaired readers in most of the experimental tasks. In addition, the dyslexic readers showed a systematic SOP gap between the auditory-phonological and the visual-orthographic modalities. The gap was found for the P2 and P3 latencies, and explained most of the variance in word recognition. The author suggested that the asynchrony between the processing rates of the visual and the auditory modalities may be an underlying cause of developmental dyslexia (Breznitz [11]).

In another study, Breznitz and Meyler [13] investigated the SOP in college-level adult dyslexic and nonimpaired readers using nonlinguistic and sublexical linguistic auditory and visual oddball tasks, and a nonlinguistic cross-modal choice reaction task. The findings pointed to longer reaction time (RT) and the latencies of P2 and P3 ERPs components occurred later in the visual as compared to auditory oddball tasks. In addition, the dyslexic readers showed delayed RT and ERPs latencies as compared to nonimpaired readers across tasks. Moreover, the gap between the ERPs latencies in the visual versus the auditory modalities for each ERPs component was larger in the dyslexic readers compared to the nonimpaired readers, particularly for the linguistic tasks. Breznitz and Misra [14] used nonlinguistic (tones and shapes), low-level linguistic stimuli (phonemes and graphemes), and higher-level orthographic and
phonological processing (a lexical decision task) to study the asynchrony in adult dyslexic readers. The
dyslexic readers showed a significantly slower RTs and longer P3 latencies than nonimpaired readers in
most of the experimental tasks, and delayed P2 latencies for the lexical decision task. In addition, the
dyslexics readers were characterized by a systematic SOP gap in the P3 latencies between the auditory-
phonological and visual-orthographic processing measures. The results were found to support the notion
of SOP asynchrony as an underlying factor in developmental dyslexia.

The hypothesis that attentional deficits may be another cognitive factor accounting for reading diffi-
culties in dyslexic readers has also been proposed in different studies (Asbjørnsen & Bryden [3]; Casco,
Tressoldi, & Dellantonio [16]; Marendaz, Valdois, & Walch [38]). Several studies have demonstrated a
correlation between performance in various visual attention tasks and reading abilities, as well as visual
attention impairments in dyslexic participants (Facoetti, Turatto, Lorusso, & Mascetti [24]; Facoetti,
Paganoni, & Lorusso [22]; Heiervang & Hugdahl [31]). Facoetti, Paganoni, Turatto, Marzola and Ma-
scetti [23] used a covert orienting paradigm in order to compare the shifting of visual attention between
dyslexic and nonimpaired children. Results of this study showed that dyslexic readers had a specific
deficit in attention shifting and maintained focused attention for shorter periods of time than their non-
impaired counterparts. The authors suggested that a specific deficit in the orienting and focusing of visual
attention may contribute to reading difficulties.

Selective attention improves the perception of high-priority stimuli as compared to less relevant stimuli
(Woldorff et al. [62]). Studies have demonstrated that dyslexic children are impaired in tasks involving
the identification of target stimuli among distracters. The relationship between selective visual attention
and linguistic performance had been studied by performing a letter cancellation task. Findings showed
that participants with the lowest performance in the cancellation task demonstrated a significantly slower
reading rate and a higher number of visual reading errors relative to participants with good performance
(Casco, Tressoldi, & Dellantonio [16]; Marendaz et al. [38]). In addition, a relationship between visual
attentional deficits and a subgroup of dyslexic children who were characterized by magnocellular visual
processing difficulties was found to be significant (Iles, Walsh, & Richardson [34]).

Several studies suggest that the spatial attention deficit observed in dyslexics is not restricted to the
visual modality. Using a dichotic listening technique, Asbjørnsen and Bryden [3] found impaired atten-
tion shifting in dyslexic readers for consonant-vowel (CV) syllables stimuli compared to nonimpaired
readers. Facoetti, Lorusso, Cattaneo, Galli, and Molteni [21] studied multimodal spatial attention in
nonimpaired and dyslexic readers by measuring RTs to lateralized visual and auditory stimuli in cued
detection tasks. They found a slower time course of focused multimodal attention in the dyslexic group.
Likewise, Hairston, Burdette, Flowers, Wood, and Wallace [30] studied the effects of task-irrelevant
auditory information on the performance of a visual temporal order judgment task. Dyslexic readers dif-
f ered significantly from nonimpaired readers specifically in that they integrated the auditory and visual
information over longer temporal intervals. The authors suggested that dyslexics are characterized by an
extended temporal “window” for binding visual and auditory cues.

The study presented here is a part of a larger research which focuses on the “asynchrony theory”
(Breznitz [12]) which has been suggested before as a cognitive marker in developmental dyslexia. The
aim of the present study was to determine whether the asynchrony that had found at the perception level
in dyslexic readers also exists in selective attention. The current study employed a paradigm which was
first adapted by Giard and Peronnet [27] for use in human ERPs studies, and has since been employed to
study the effects of multisensory integration (audiovisual stimuli), as compared to unimodal stimulation
(auditory or visual stimuli) on attention (e.g., Senkowski, Talsma, Herrmann, & Woldorff [47]; Talsma
& Woldorff [56]). The method entails the randomized successive presentation of unisensory auditory, unisensory visual, and multisensory audiovisual stimuli.

Behavioral RT and accuracy parameters were collected from nonimpaired and dyslexic readers, and the earlier ERPs components were examined since they are thought to reflect attentional modulations (Woldorff et al. [62]). In addition, as it is not clear whether the dyslexic readers deficits are an outcome of deficits only in the language domain (Ramus [42]) or can be seen also as domain general deficits (Stine [50]; Tallal [55]), another aim was to verify whether asynchrony of selective attention in dyslexic readers is manifested in the case of alphabetic stimuli (pre-lexical CV syllables) and nonalphabetic stimuli (pictures and sounds of animals) as well.

2. Method

2.1. Participants

Participants were 50 native Hebrew-speaking students at the University of Haifa, 25 dyslexic readers and 25 nonimpaired readers. Dyslexic readers were recruited from Yahel, the student support center for learning disabilities at the University of Haifa. All dyslexic participants were at least \(-1.5\) standard deviations (S.D.) below average on the MATAL (2004) reading disabilities normative test. All participants were paid volunteers and the two groups were matched for age (range of 20–28 years) and general ability. All participants were right-handed and had no history of neurological problems, psychiatric disorders, attention deficit or hyperactivity symptoms, and no significant hearing or vision complaints.

2.2. Baseline measures

The classification of participants into nonimpaired readers and dyslexic readers groups was based on the following behavioral measures:

One-Minute Test for Words (Shatil [48]): Participants were asked to read a list of real single words as quickly and as accurately as possible within the space of one minute. The list contained 100 real Hebrew words arranged in order of increasing length and decreasing frequency. Accuracy scores were based on the number of words read correctly and reading rate was calculated according to the number of words read per minute.

One-Minute Test for Pseudowords (Shatil [49]): The participants were asked to read 100 pseudowords arranged in order of increasing length. Same parameters were collected like on the former test.

Silent Text Reading Fluency and Reading Comprehension Test (The Center for Psychometric Tests [57]): The Silent text reading fluency parameter was based on the mean reading time per word. Participants were asked to silently read a passage as quickly as possible. In the Reading comprehension test the participants were asked to answer five multiple-choice questions and 12 yes/no questions related to the passage. Comprehension scores were based on the total number of correct answers.

Digit Symbol (WAIS–R, Wechsler [59]): The test was used to evaluate speed of performance. The standard scores of each participant were recorded.

Rapid Alternating Stimulus Naming Tests (Breznitz [10]; based on Denckla & Rudel [18]): The Rapid Automatized Naming (RAN) tests were used to evaluate verbal speed of processing. The participants were instructed to name a list of 50 recurring Hebrew letters, and a list of 50 recurring objects. A Rapid Alternating Stimuli test (RAS) included a list of 50 alternating stimuli. Participants were asked
to name all stimuli on each test, as quickly and as accurately as possible. Time and number of errors were recorded for each test.

**Digit Span** (Wechsler [60]): The standard scores of each participant were recorded in order to evaluate memory processes.

**Parsing Test** (Breznitz [9]): The test used to assess orthographic skills. Participants were presented with a list of 46 character strings, each consists few Hebrew words. They were asked to parse each string into its constituent words by marking vertical lines between the words. The total time of task performance and the number of correctly parsed strings were recorded.

**Phonemic Segmentation Test** (Shatil [50]): The task used to assess phonemic awareness. A list of 16 pseudowords was read aloud by the experimenter, one at a time, and the participants had to segment each pseudoword into its constituent phonemes (consonants and vowels). Average time per item and average accuracy across both tests were recorded.

**Phonemic Deletion Test** (Shatil [50]): A list of 25 pseudowords was read aloud by the experimenter, one at a time, and the participants were asked to vocalize each pseudoword by omitting a designated phoneme located at the beginning, in the middle, or at the end of a word. Average time per item and average accuracy across both tests were recorded.

**Attention Network Test** (Fan, McCandliss, Sommer, Raz, & Posner [26]): A short version of the Attention Network Test (ANT) used to compare attentional capacities between the two groups. Both groups underwent a single 10-minute testing session in order to evaluate the three attentional systems: alerting, orienting, and executive attention. The stimuli consist of a row of five horizontal black lines, with arrowheads pointing left or right, set against a gray background. The target located in the center is also a left or right-facing arrowhead and is flanked on either side, facing either in the same direction (congruent condition) or the opposite direction (incongruent condition) by the rows of horizontal lines. Participants were asked to identify the direction of the centrally presented arrow by pressing one button for the left or a second button for the right.

Cues consist of a 100 millisecond (msec) asterisk presented 400 msec before the target. The task includes several cue conditions: (1) no-cue, in which participants are shown a cross that is the same as the first fixation for 100 msec; (2) central-cue, which is at the central fixation point; (3) spatial-cue, where the cue is presented right on the target location (either above or below the central fixation point). The presentation of trials is randomized. Participants are instructed to focus on a centrally located fixation cross throughout the task, while responding as quickly and as accurately as possible.

2.3. Experimental tasks

The experiment included two tasks, a nonalphabetic task and alphabetic task. Each task included 70 visual stimuli, 70 auditory stimuli, and 70 audiovisual stimuli (simultaneous presentation of the auditory and visual components). Both tasks included a central presentation of all the stimuli.

**Nonalphabetic Task**: Each of the 70 stimuli for each modality (visual/auditory/audiovisual) contained two types of stimuli, a dog and a cat. Two line drawings of animals, taken from Snodgrass and Vanderwart [51] and standardized for familiarity and complexity, were used as the nonalphabetic visual stimuli. The visual stimuli were always grey presented against a black background.

Two animals sounds (a cat meow and a dog bark) adapted from Fabiani, Kazmerski, Cycowicz, and Friedman [19], served as the auditory stimuli. These sounds were of uniquely identifiable vocalizations corresponding to the two animal drawings. The auditory stimuli were transmitted through inplug head-phones at an amplitude of 75 dB. To avoid confounds associated with potential variability in auditory
sensitivity, participants were allowed to adjust their own volume setting when they were first introduced with the task. The sounds were modified so that each had a duration of 125 msec, exactly like the duration of the visual stimuli presentation. Visual stimuli were 2 × 2 cm width and height. The inter-stimulus interval (ISI) ranged between 600 to 800 msec in order to prevent fixed responses by the participants.

A new randomized order of tasks was counterbalanced for each participant, and the presentation of stimuli was also randomized within each task. Throughout the experiment, the participants were instructed to focus their attention on a fixation point appeared on the center of the computer screen. For a dog stimuli (auditory/visual/audiovisual) the participants were required to press one key (key “1”) with their right index finger and another key (key “2”) with their right middle finger for identifying a cat stimuli (auditory/visual/audiovisual), while reacting as quickly and as accurately as possible. No counterbalance between the two fingers has been done.

Alphabetic Task: The alphabetic task was identical to the nonalphabetic task, excluding the stimuli employed. Here, two CV syllables were used. Two stop consonants, b and p, were paired with the vowel /a/ and formed the syllable /ba/ (/ב/ in Hebrew) and the syllable /pa/ (/פ/ in Hebrew). The auditory stimuli, /ba/ and /pa/, were recorded through a microphone by a male voice (a native Hebrew speaker) with constant intonation and intensity. The recordings were digitized for editing on a computer equipped with a standard sound board. Each stimulus was aligned using GoldWave v5.05 software (GoldWave Inc., 2003) in order to control stimulus duration and volume amplitude. Duration of the stimuli presentation and the ISI were identical to those detailed in the nonalphabetic Task. The participants were asked to press one key (key “1”) for all /ba/ stimuli and another key (key “2”) for all /pa/ stimuli.

2.4. Electroencephalographic (EEG) parameters

The participants were connected to a 64 channel Electroencephalograph (EEG). The EEG signals were recorded using 64 scalp electrodes with a Biosemi System (see Fig. 1). Scalp electrodes were referenced to an electrode on the chin and grounded to an electrode on the mastoid. Eye movements were monitored by a separate electrode placed below the left eye. EEG data was sampled at 256 Hz by using Biosemi ActiView software (Cortech Solutions, LLC), which is designed to display all Active Two channels on screen and save all the data. During data collection, electrode impedance was kept below 5 KΩ by prepping scalp areas with a mildly abrasive cleanser (NuPrep) and by using an electrolyte gel (Electro-gel). Signals were filtered at 0.1–100 Hz. Continuous EEG recordings were segmented into 1.75-second epochs (448 samples, fs = 256 Hz). Each epoch contained 64 pre-stimulus samples (= 250 msec) for establishing baseline activity and 384 post-stimulus samples. The EEG data was processed using Brain Vision Analyzer (Brain Products, GmbH), and horizontal as well as vertical eye movements were corrected via Gratton, Coles and Donchin’s algorithms [29], implemented in the Vision Analyzer (version 1.05). The data were filtered offline using a bandpass of 0.1 to 20 Hz, and baseline corrections were performed. Experimental conditions were averaged separately for each subject, rejecting any trials with incorrect behavioral responses. Grand average waveforms were computed across all participants.

2.5. Procedure

As a first step, all participants were tested with the behavioral baseline tests and the reading level of each group was confirmed. Then the two groups of participants completed the two experimental tasks. The participants were seated in a sound-attenuated chamber inside the laboratory. All of the stimulus
3. Results

3.1. Background behavioral reading and cognitive measures

Several independent t-tests were conducted in order to determine group differences for each of the background measures. As can be seen, significant differences between the two groups were obtained for several reading parameters, in which the dyslexic readers achieved significantly lower scores than the nonimpaired readers (see Table 1). The dyslexic readers also achieved significantly lower scores compared to the nonimpaired readers in most of the cognitive measures (see Table 2).
Fig. 2. A scheme of the alphabetic task.

| Table 1: Reading measures data for dyslexic and nonimpaired readers |
|-----------------------------------------------|-------------------|-------------------|
|                                                | Nonimpaired        | Dyslexic readers   | t     |
|                                                | group              | group             |       |
| Mean | S.D. | Mean | S.D. |       |
| One-Minute Test for Words – total number of words. | 112.00 17.18 | 69.07 20.68 | -8.44*** |
| One-Minute Test for Words – number of words read correctly. | 111.04 16.39 | 65.63 20.71 | -8.87**** |
| One-Minute Test for Pseudowords – total number of read words. | 63.64 13.85 | 41.92 9.05 | -6.86*** |
| One-Minute Test for pseudowords – number of correct words. | 59.89 15.68 | 27.50 11.05 | -8.70*** |
| Silent Text Reading Fluency – number of words per min. | 212.05 54.69 | 128.83 30.12 | -6.89*** |
| Reading Comprehension – correct answers out of 20 questions. | 14.67 2.40 | 13.00 3.70 | 0.06 |

Note 1: *p < 0.05; ** p < 0.01; *** p < 0.001.

3.2. Attentional baseline measures

The analysis of the three attentional networks produced by the ANT was conducted for correct trials as a function of cue and flanker condition. Here, one-way analysis of variance (ANOVA) was used in order to study the differences between the nonimpaired and the dyslexic readers.

The alerting effect was calculated by subtracting the mean RT of the center-cue conditions from the mean RT of the no-cue conditions, and the orienting effect was calculated by subtracting the mean RT of the spatial-cue conditions from the mean RT of the center-cue conditions. The conflict resolution effect was calculated by subtracting the mean RT of all congruent flanking conditions, summed across...
Table 2
Cognitive background data for dyslexic and nonimpaired readers

|                          | Nonimpaired readers group | Dyslexic readers group | t    |
|--------------------------|---------------------------|------------------------|------|
|                          | Mean          | S.D.               | Mean   | S.D.   |      |
| **Digit Symbol – raw score** | 82.60         | 10.75              | 73.23   | 15.16  | -2.63** |
| **RAN Letters – time**    | 21.78         | 3.25               | 25.78   | 4.16   | 3.95*** |
| **RAN Letters – errors**  | 0.07          | 0.38               | 0.30    | 0.54   | 1.78  |
| **RAN Objects – time**    | 31.73         | 5.07               | 40.64   | 6.30   | 5.82*** |
| **RAN Objects – errors**  | 0.10          | 0.41               | 0.08    | 0.27   | -0.27 |
| **RAS – time**            | 21.87         | 2.86               | 28.90   | 5.98   | 5.57*** |
| **RAS – errors**          | 0.03          | 0.18               | 0.23    | 0.51   | 1.82  |
| **Digit Span – standard score** | 12.42      | 3.08               | 9.00    | 2.76   | -4.38*** |
| **Parsing Test – time**   | 184.32        | 47.78              | 334.58  | 110.34 | 6.61*** |
| **Phonemic Segmentation – time** | 92.06   | 33.64              | 134.63  | 55.19  | 3.34** |
| **Phonemic Segmentation – correct (out of 16)** | 14.53 | 2.76               | 13.52   | 3.05   | -1.26 |
| **Phonemic Deletion – time** | 127.83    | 34.83              | 218.64  | 54.30  | 7.01*** |
| **Phonemic Deletion – correct (out of 25)** | 23.67 | 4.57               | 22.39   | 4.13   | -1.10 |

Note 1: * p < 0.05; ** p < 0.01; *** p < 0.001.

cue types, from the mean RT of all incongruent flanking conditions. No significant between groups differences in any of the attentional measures were found. See Fig. 3.

3.3. Behavioral parameters of the experimental tasks in the dyslexic and nonimpaired readers

Several one-way ANOVA tests were performed to examine asynchrony between the auditory and the visual modalities. Statistical analysis for audiovisual stimuli has not been performed in the current study. As can be seen in Table 3, dyslexic readers demonstrated a longer RT than nonimpaired readers for visual stimuli on the alphabetic task. No other significant differences were found for the RTs between the two groups.

Behavioral asynchrony was examined by calculating a gap factor between the auditory and the visual RTs in each group and task, using paired-samples t-tests. As can be seen in Table 4, the dyslexic readers group was characterized by a significantly wider time gap on the alphabetic task. This wider time gap was characterized by a faster RT for auditory stimuli and a slower RT for visual stimuli. For the nonimpaired group, the same RTs were found for both visual and auditory stimuli. No significant gap factor was found within the groups on the nonalphabetic task, both groups of readers showed nonsignificant differences between the RTs for auditory and the visual stimuli. An additional analysis was performed in order to study accuracy of responses on each group. The dyslexic group showed lower hit rates for visual stimuli [F(1, 54) = 4.46; p < 0.05] on the alphabetic task. See Table 5 for additional data.

3.4. ERPs parameters in the dyslexic and nonimpaired readers

One-way ANOVA tests were calculated separately in order to evaluate the ERPs components for the nonimpaired and the dyslexic readers. These calculations were performed for both the nonalphabetic and alphabetic tasks.
Fig. 3. Comparison between the nonimpaired and the dyslexic readers on the ANT.

Table 3

| Task         | Stimuli type | Nonimpaired readers | Dyslexic readers | df | F    | Sig   |
|--------------|--------------|---------------------|------------------|----|------|-------|
| Nonalphabetic| Auditory     | 488.48 (50.51)      | 493.30 (53.94)   | 1, 49 | 0.12 | 0.73  |
|              | Visual       | 473.75 (46.61)      | 475.71 (52.24)   | 1, 49 | 0.02 | 0.88  |
| Alphabetic   | Auditory     | 485.95 (38.08)      | 486.01 (50.52)   | 1, 49 | 0.34 | 0.57  |
|              | Visual       | 485.52 (49.79)      | 512.09 (30.21)   | 1, 49 | 0.62 | 0.02  |

Means and standard deviation for reaction times in milliseconds.

Table 4

| Task         | Group of readers | Gap factor – Mean | S.D. | t    | df  | Sig |
|--------------|------------------|-------------------|------|------|-----|-----|
| Nonalphabetic| Dyslexics        | −26.08            | 48.86 | −2.72 | 25  | 0.01|
|              | Nonimpaired      | 0.43              | 35.60 | 0.06  | 25  | 0.95|
| Alphabetic   | Dyslexics        | 17.59             | 86.04 | 1.08  | 25  | 0.29|
|              | Nonimpaired      | 14.74             | 68.16 | 1.14  | 25  | 0.26|

Means and standard deviation for gap factors in milliseconds.
Table 5
Response accuracy (%) of the nonimpaired readers and dyslexic readers according to task and stimuli type

| Task       | Stimuli type | Nonimpaired readers | Dyslexic readers | df  | F   | Sig  |
|------------|--------------|---------------------|------------------|-----|-----|------|
| Nonalphabetic | Auditory     | 81.43 (16.27)       | 75.56 (12.85)    | 1.49| 2.24| 0.14 |
|            | Visual       | 78.83 (14.56)       | 75.20 (9.39)     | 1.49| 1.22| 0.27 |
| Alphabetic  | Auditory     | 80.83 (10.96)       | 75.71 (13.03)    | 1.49| 2.52| 0.12 |
|            | Visual       | 82.45 (15.50)       | 73.78 (15.22)    | 1.49| 4.46| 0.04 |

Means and standard deviation for response accuracy in percentage.

Fig. 4. C2 electrode grand average for auditory nonalphabetic stimuli: The continuous line represents the nonimpaired readers group and the dashed line represents the dyslexic readers group.

**Auditory:** Auditory stimuli in the nonalphabetic task elicited an early N1 component distributed frontally and laterally to the right hemisphere. The N1 component occurred approximately 124 msec after stimulus onset in each of the groups. However, the nonimpaired readers demonstrated enhanced activation for this component relative to their dyslexic counterparts. These differences were found in the Fz and C2 electrodes (see Fig. 4). The N2 component was found to be larger in the nonimpaired group and was distributed frontally, with differences between the groups emerging in the Fz electrode. No significant differences were found between the two groups in the alphabetic task for auditory stimulation.

In addition, the nonimpaired readers demonstrated a correlation between the AFz amplitude in the N1 component and the correct response parameter ($r = 0.41, p < 0.03$). Also, a significant correlation was found between the latency of Fp2 (right hemisphere) and the percentage of correct responses ($r = 0.40$, ...
Fig. 5. PO8 electrode grand average for visual alphabetic stimuli: The continuous line represents the nonimpaired readers group and the dashed line represents the dyslexic readers group.

$p < 0.03$). These correlations were not found for the dyslexic readers group. The dyslexic group, however, demonstrated a correlation between the latency of the N1 component at the C4 electrode (right hemisphere) and behavioral RT ($r = -0.39, p < 0.03$).

In the alphabetic task, the nonimpaired readers demonstrated a correlation between the latency of the N1 in C3 electrode (left hemisphere) and the percentage of correct responses ($r = 0.54, p < 0.01$), while the dyslexic readers demonstrated a significant correlation between the amplitude of the N1 component in the C3 electrode and the percentage of correct responses parameter ($r = -0.49, p < 0.01$).

**Visual:** Only one site was found to be different between the two groups for alphabetic visual stimuli. The nonimpaired readers demonstrated higher activation in the P1 component, which appeared in the PO8 electrode (right hemisphere). No additional differences were found for visual stimuli. See Fig. 5. In addition, the nonimpaired readers demonstrated a correlation between the latency of the FCz electrode in the P1 component ($r = 0.38, p < 0.04$) and hit rates.

### 3.5. ERPs gap factors

Paired sample $t$-tests were performed to study asynchrony within the two groups of readers. Significant gaps (asynchrony) between the auditory and the visual ERPs latencies were found only for the dyslexic readers group on the alphabetic stimuli. Table 6 reports only significant gap factors, and as can be seen the dyslexic group showed significant time gaps on the N1 component on the PO7 and PO8 electrodes. The dyslexic readers also showed a time gap on the N2 component of PO7 electrode. The gap found on the N1 pointed for shorter latencies on the auditory modality. The time gap found for the N2 was characterized by a shorter latency of the visual modality compared to auditory latency.
4. Discussion

The main aim of the current study was to investigate the claim of the “asynchrony theory” (Breznitz [11,12]) that the SOP gap between the visual and the auditory modalities at the perceptual level in dyslexic readers also exists in selective attention. For this purpose, native Hebrew-speaking adult non-impaired and dyslexic readers participated in this study, while both behavioral and electrophysiological parameters were used. The ERPs methodology was used to follow changes in cortical electrical activity related to cognitive processes, and a main focus has been given to the earlier ERP components, such as P1 and N1, since they are considered to be attention-related markers (Heinze et al. [32]; Mangun [37]; Wijers, Mulder, Gunter, & Smid [61]; Woldorff et al. [62]).

The main finding of the current study is that adult dyslexic readers demonstrate asynchrony between the visual and the auditory modalities when they are required to activate attentional resources and when selective attention is studied. Breznitz [12] pointed at a significant processing time gap between the two modalities which are activated at the perceptual level in the process of reading. The behavioral data in the current study points to a processing time gap in the dyslexic readers group only for alphabetic stimuli. The RTs were significantly longer when alphabetic visual stimuli were presented as compared to the auditory ones, while the nonimpaired readers showed similar behavioral SOP for the auditory and visual stimuli.

It is conceivable that the differences between the two groups derive from an impaired hemispheric collaboration which is necessary for processing stimuli which are centrally presented. The impaired hemispheric collaboration might slow down the processing speed of the visual modality when alphabetic stimuli are being selected for entrance into the cognitive system. It is well known that a complex cognitive task demands integration of information from both cerebral hemispheres, and it was suggested that developmental dyslexia may be attributed to impaired interhemispheric communication (Gladstone, Best, & Davidson, 1989). In fact, impaired callosal transfer may disrupt the cognitive processes which are necessary for reading. In their study, Miller-Shaul and Breznitz [39] found a slower interhemispheric transfer time in elementary school-aged children with dyslexia compared to nonimpaired readers. A low hemispheric collaboration may reduce the SOP and according to Perfetti [41], the stimulus being processed while reading might encounter a bottleneck that occurs when limited attentional and memory resources become overloaded. Hence, the efficiency of decoding written codes is reduced.

The ERPs findings of the current study support the asynchrony phenomenon in dyslexic readers as well. Similar to the behavioral data, the main results derived from the ERPs came from the alphabetic task. The time gaps were observed in the dyslexic readers group between the N1 and N2 latencies when
processing auditory and the visual stimuli. The N1 latencies were significantly longer when visual alphabetic stimuli were processed as compared to the auditory ones. Shorter latencies for auditory stimuli, as compared to the visual latencies, were found in the occipital (PO7 and PO8) electrodes. No between modalities time gap was found in the nonimpaired readers group. These findings are in line with a study conducted lately by Sela [46], who presented auditory and visual stimuli to investigate the effect of one modality on the SOP of the second modality. Using unimodal and cross-modal presentations, significant differences were found between the dyslexic readers and the nonimpaired readers. The results were discussed in terms of difficulty to synchronize the processing between the visual and the auditory modalities in developmental dyslexia.

The fact that the latencies for visual stimuli at the early stages of processing information were longer is in line with the “magnocellular theory.” Stein and Walsh [54] argue that the reading disabilities exhibited by dyslexic readers are a result of abnormalities of the magnocellular component of the visual system. The magnocellular component is specialized for processing fast temporal information and the magnocellular stream culminates in the posterior parietal cortex, which is known to be an important area in the visual attention system. The authors claimed that dyslexics may be unable to process fast incoming sensory information from the visual modality.

In general, the evidence of deficits in spatial attention in adult dyslexics is supported by the findings of previous studies. For example, Facoetti, Corradi, Ruffino, Gori, and Zorzi [20] studied preschoolers with and without familial risk for developmental dyslexia. The children were tested for phonological skills, rapid automatized naming, and visual spatial attention. Children at risk presented deficits in both visual spatial attention and syllabic segmentation. The authors concluded that visuo-attentional as well as perisylvian-auditory dysfunctions might affect reading acquisition. In another study, Facoetti and colleagues [25] found that dyslexics with impaired nonword reading selectively showed a lack of attentional inhibition for targets at an uncued location in the right visual field. The authors suggested that focused visuo-spatial attention may be crucial for nonword decoding.

Interestingly, in the dyslexic group, unlike the N1 latencies, the N2 latency in PO7 electrode was shorter for the visual stimuli as compared to the auditory one. Is it possible that compensated adult dyslexics’ visual system learned over the years to make an effort and to accelerate its processing speed in order to overcome the between-modalities asynchronous processing. This issue needs to be studied in depth in the future. The findings demonstrate that a between-modalities processing time gap continues to exist in the adult dyslexic readers from the selective attentional level, as supported by the current study, to perception and working memory processing (see Breznitz [12]; Breznitz & Misra [14]). In the nonimpaired readers, the modalities operate on a similar time scale from the selective attentional level, as supported here, to perception processing and output levels (see Breznitz & Misra [14]).

In addition to the asynchrony which was found in the dyslexic readers group, the dyslexic readers demonstrated a negative correlation between the amplitude of the N1 in the C3 electrode and percentage of correct responses. The nonimpaired readers showed a link between the latency of the N1 in C3 electrode and the percentage of correct responses. Taken together, these findings may point to a less efficient left hemisphere in developmental dyslexia. These findings are in line with former studies which explored laterality effects in dyslexic readers compared to nonimpaired readers (Brunswick & Rippon [5]; Hugdahl, Helland, Færevaag, Lyssand, & Asbjørnsen [33]; Moncrieff & Black [40]).

In conclusion, the current study supports the notion that dyslexic readers demonstrate an asynchrony between the auditory and the visual modalities when processing alphabetic stimuli. These findings may point to the necessity of synchronized auditory and visual modalities for intact reading and enhance our assumption that automatized reading processes depend on synchronization between the auditory and
the visual modalities, even when it comes to selective attention. The evidence that the dyslexic readers in the current study demonstrated the asynchrony in selective attention only for alphabetic stimuli requires further study.

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