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Research report

# Is the visual analyzer orthographic-specific? Reading words and numbers in letter position dyslexia

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ARTICLE INFO

*Article history:*
Received 7 July 2008
Reviewed 6 February 2009
Revised 9 August 2009
Accepted 13 August 2009
Action editor Sergio Della Sala
Published online 27 August 2009

*Keywords:*
Dyslexia
Letter position dyslexia
Developmental dyslexia
Numbers
Hebrew

ABSTRACT

Letter position dyslexia (LPD) is a deficit in the encoding of letter position within words. It is characterized by errors of letter migration within words, such as reading *trail* as *trial* and *form* as *from*. In order to examine whether LPD is domain-specific, and to assess the domain-specificity of the visual analysis system, this study explored whether LPD extends to number reading, by testing whether individuals who have letter migrations in word reading also show migrations while reading numbers. The reading of words and numbers of 12 Hebrew-speaking individuals with developmental LPD was assessed. Experiment 1 tested reading aloud of words and numbers, and Experiment 2 tested same–different decisions in words and numbers. The findings indicated that whereas the participants with developmental LPD showed a large number of migration errors in reading words, 10 of them read numbers well, without migration errors, and not differently from the control participants. A closer inspection of the pattern of errors in words and numbers of two individuals who had migrations in both numbers and words showed qualitative differences in the characteristics of migration errors in the two types of stimuli. In word reading, migration errors appeared predominantly in middle letters, whereas the errors in numbers occurred mainly in final (rightmost) digits. Migrations in numbers occurred almost exclusively in adjacent digits, but in words migrations occurred both in adjacent and in nonadjacent letters. The results thus indicate that words can be selectively impaired, without a parallel impairment in numbers, and that even when numbers are also impaired they show different error pattern. Thus, the visual analyzer is actually an orthographic visual analyzer, a module that is domain-specific for the analysis of words.



## 1. Introduction

Individuals with letter position dyslexia (LPD) typically make within-word transpositions such as reading *diary* instead of *dairy*, or *bread* instead of *beard* (Friedmann and Gvion, 2001, 2005; Friedmann and Rahamim, 2007). This dyslexia results from a deficit in the visual analysis system, which selectively impairs the ability to encode the relative position of letters in the word. The current research explored whether this deficit is domain-specific to orthographic-verbal material or whether it also extends to numbers. A selective deficit in words but not in numbers would indicate that a letter-position-encoding function exists that is specific to words, and that the early stage of visual analysis of words is actually

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doi:10.1016/j.cortex.2009.08.007

orthographic visual analysis, specific to orthographic-verbal input.

This early stage of word reading, visual analysis, is responsible for the encoding of abstract letter identities (Coltheart, 1981, 1987; Evett and Humphreys, 1981; Bigsby, 1988), for encoding the relative position of letters within words (Ellis et al., 1987; Humphreys et al., 1990; Ellis, 1993; Peressotti and Grainger, 1995), as well as for setting the attentional window that allows for the allocation of attention to a single word (Coltheart, 1981; Shallice, 1988; Ellis and Young, 1996). A deficit in each of these functions causes a different type of peripheral dyslexia, with different characteristics: deficits in letter identity result in letter substitutions or omissions (as in the case of visual dyslexia, Marshall and Newcombe, 1973; Lambon Ralph and Ellis, 1997; Cuetos and Ellis, 1999; Biran et al., 2003; and in visual letter agnosia, which some researchers term ''pure alexia'' – Déjerine, 1892; Goldstein and Gelb, 1918; Gainotti et al., 1974). A deficit in the encoding of the relative position of letters within words results in migration of letters within words (LPD, Friedmann and Gvion, 2001, 2005; Friedmann and Rahamim, 2007; Friedmann and Haddad-Hanna, in press). A deficit in letter-to-word binding results in migrations of letters between words (as is the case in attentional dyslexia, Shallice and Warrington, 1977; Saffran and Coslett, 1996; Hall et al., 2001; Davis and Coltheart, 2002; Friedmann et al., in press).

Two individuals with a selective acquired deficit of letter position within words, without letter identity errors and without letter migrations between words, were reported by Friedmann and Gvion (2001). In a variety of tasks, their main errors were letter transpositions, namely, migrations of letters within words. The transpositions occurred almost exclusively in middle letters, whereas first and final letters remained in their original positions. Errors tended to occur mainly in ''migratable'' words, i.e., words in which transposition of middle letters can create another existing word. Friedmann and Rahamim (2007) reported 11 individuals with developmental form of LPD who showed a very similar pattern of reading, of migrations of middle letters within words; Friedmann and Haddad-Hanna (in press) reported a similar pattern in 3 readers of Arabic with developmental LPD and one with acquired LPD.

These studies presented cases of pure letter-position encoding deficit without other errors types. Errors of letter order were also reported in the reading of several individuals with various types of acquired dyslexia who made transpositions in addition to other types of reading errors, and whose deficit was not selective to letter position encoding. These individuals, when asked to name a letter in a sequence, occasionally named another letter that was located in a different position in the sequence, or made transpositions within words and letter sequences. This was reported for an individual with deep dyslexia (Marshall and Newcombe, 1973); for individuals with positional dyslexia and attentional dyslexia (Shallice and Warrington, 1977; Katz and Sevush, 1989; Price and Humphreys, 1993; Hall et al., 2001; Humphreys and Mayall, 2001) and for an individual with visual dyslexia (Biran et al., 2003). McCloskey and Rapp (2000a, 2000b) reported a woman who frequently misperceived the orientation and ordering of objects, letters and words. In reading single words she incorrectly perceived the location of letters when she read words or named letters. She had letter transposition errors but this was not the main type of error she made in reading, and she also had a general visual-localization deficit. Skilled readers also show letter transpositions in reading, and misperceive migratable nonwords as their transposed counterpart (Andrews, 1996; Perea and Lupker, 2004), findings that led to the development of models that accommodate encoding of letter position within strings (the SERIOL model, Whitney, 2001; Whitney and Cornelissen, 2005; Bayesian Reader theory, Norris et al., 2006; the overlap model, Gomez et al., 2008).

None of these studies directly compared transposition errors in reading whole words and numbers. One exception, which did not reach conclusive results, is the study by Friedmann and Gvion (2001). This study tested the reading of numbers by two individuals with acquired LPD and found that the participants' performance in the same–different decision task was significantly better in numbers than in words. The participants did make, however, errors in reading numbers aloud, which were not digit migrations, but rather doublings of digits. It is hard to determine whether these doublings resulted from migrations of a digit without deletion of the digit from its original position, or from digit substitution, and therefore the two case studies cannot be taken as a clear-cut evidence for a dissociation between letter position encoding in words and numbers.

Many case studies of other types of dyslexia report that the difficulties in reading words are accompanied by a similar impairment in the reading of Arabic numerals.[1] One study reported an association in peripheral dyslexia: Katz and Sevush (1989) described an individual with what they termed ''positional dyslexia'', who had difficulties in reading the first symbol in a sequence – be it a letter or a digit. Other studies described an association between number and word-reading impairments in central dyslexias. Cohen et al. (1994) described a case of deep dyslexia which affected numbers as well as words. Denes and Signorini (2001) reported an individual with phonological dyslexia who could read words but had impaired reading of nonwords and numbers (a finding that might be explained by the assumption that numbers are read, like nonwords, via a sublexical route).

However, impaired reading of words is not always associated with impaired number reading. In fact, the very first reported case of visual letter agnosia (''pure alexia''), described by Déjerine (1892), had spared reading of digits, and this dissociation was found in later studies as well (Cohen and Dehaene, 1995; Starrfelt, 2007). Friedmann and Nachman-Katz (2004) described a Hebrew-reading child with a severe neglect dyslexia who could still read Arabic numbers normally, and Nachman-Katz and Friedmann (2007) reported 18 additional children with this pattern. Ablinger et al. (2006) treated an aphasic patient (PK) who had difficulties in reading numbers aloud. The patient also had difficulties in word reading (she had deep dyslexia), but it seems that her number reading was

[1] The term ''Arabic numeral'' or ''Arabic number'' relates to the number symbols 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, which were brought to Europe by the Italian mathematician Fibonacci from the Hindu-Arabic system. Interestingly, the number symbols that are currently used in Arabic are different.

far worse than her word reading. This case is special in that it shows an opposite dissociation, in which number reading is worse than word reading. Cipolotti et al. (1995) described the case of SF, who could read words even when they were number names, but not Arabic numerals. Interestingly, SF's comprehension and production of numbers was intact; it was only his transcoding from Arabic numerals to spoken number words which was impaired. However, only the numbers 1–10 were thoroughly tested in this study, and there is some evidence that the production of single digits may be different from the production of multi-digit numbers (Girelli and Delazer, 1999; Marangolo et al., 2004; Dotan and Friedmann, 2007), so it may be speculated that a similar difference exists in the reading modules as well. Finally, several studies reported individuals with dyslexia, without specifying the type of dyslexia or its exact characteristics, whose impairment was limited to words – with spared reading of Arabic numbers (Albert et al., 1973; Hécaen and Kremin, 1976; Lühdorf and Paulson, 1977; Anderson et al., 1990; Sakurai et al., 2006).

Several studies reported dissociations where reading aloud of both words and numbers was impaired, but the comprehension of printed Arabic numbers was spared, which indicates that the input reading modules, at least as far as numbers were concerned, remained intact (Miozzo and Caramazza, 1998; Cohen and Dehaene, 2000; Dalmás and Dansilio, 2000). Other studies discovered different processing patterns for numbers and words, even when the words denote numeric values (Besner and Coltheart, 1979; Mason, 1982; Fias et al., 2001; Damian, 2004). Some studies that focus on the single-symbol level also imply that letters and digits are processed differently (see a review in Hollender and Peereman, 1987), and brain imaging studies also provide evidence in favor of different processing mechanisms for words and numbers (see a review in Starrfelt, 2007).[2]

In summary, several dissociations were found between the reading of words or letters and the reading of Arabic numerals, but there was no report of such a dissociation in letter position dyslexia. Furthermore, most of these reports were of acquired dyslexias, and we know of only one report of a word-number dissociation in developmental peripheral dyslexias – of children with developmental neglect dyslexia who read numbers normally (Friedmann and Nachman-Katz, 2004; Nachman-Katz and Friedmann, 2007).

In this study we explore the processing of numbers and words by comparing the reading of words and numbers in 12 individuals with developmental LPD. In the first part of the study, in which 11 of them participated, we asked whether the deficit is orthographic-specific, namely, constrained to words and letter sequences, or whether it extends to numbers, which are also part of a conventional written system. In the second part of the study we compared the characteristics of errors in word and number reading for two participants who show migrations in both words and numbers. These issues might have implications for the characterization of the deficit in developmental LPD, as well as for the domain-specificity of the visual analysis system.

## 2. Experimental investigation

### 2.1. *Part A: reading words and numbers in LPD*

#### 2.1.1. *Method*

2.1.1.1. Participants. Eleven individuals with a significant rate of letter position errors in reading participated in this part of the study. They were the participants whose LPD was reported in detail in Friedmann and Rahamim (2007). The participants were 10 children and adolescents aged 9;4–15;9, five girls and five boys, and one man aged 29;10. All but one had no history of neurological impairment, and one probably had brain lesion prior to reading acquisition (he had a transient hemiplegia event around age 6), hence their dyslexia was considered to be developmental. Table 1 presents background information on the participants. For the selection of participants to this study, we used the TILTAN test battery (Friedmann and Gvion, 2003), which was developed to identify subtypes of dyslexia. The screening part of the TILTAN uses oral reading of 128 single words, 30 word pairs, and 30 nonwords. The test includes words of various types that can reveal the different types of dyslexia: irregular words and potentiophones[3] for the identification of surface dyslexia; nonwords for the identification of phonological and deep dyslexia; words (and nonwords) that can be read as other words by neglecting one side of the word, for the identification of neglect dyslexia; words with many orthographic neighbors for visual dyslexia; morphologically complex words for deep and other dyslexias; word pairs in which between-word migration creates other existing words for attentional dyslexia, and finally, migratable words (and nonwords) for the identification of LPD. The 11 participants who were included in this study had a significant rate of migration errors (in more than 10% of the words) in the TILTAN word-reading screening

[2] Additional information comes from studies of attentional dyslexia. Shallice and Warrington (1977), in their pioneering study on attentional dyslexia, found that letter recognition was slowed down when a letter was flanked by other letters (two on each side), but not when it was flanked by digits. The same was found by Saffran and Coslett (1996). They found that the reading of words was worse when they were flanked with two letters than when they were flanked with two digits. This finding was replicated by Hall et al. (2001) with GK (but such a difference was not found in Humphreys and Mayall, 2001). Still, these symbol-level studies do not necessarily prove that words and numbers are processed by different mechanisms: one can also interpret them as showing that letters and digits are perceived as separate categories, and that it is easier to distinguish between symbols of different categories than between symbols within the same category, a phenomenon observed with other types of stimuli as well (Warrington et al., 1993). In fact, this was the way Shallice and Warrington (1977) interpreted their findings.

[3] *Potentiophones* are pairs of words that are written differently and sound differently. However, because they contain homophonic letters (and are usually underspecified for vowels), if read solely via the grapheme-to-phoneme conversion route one word can be read aloud instead of the other. A relevant example in English is the word *now*: when read aloud via the sublexical route, this word may erroneously be pronounced like the words *no* and *know* (Friedmann and Lukov, 2008).

**Table 1 – Background information on the participants with LPD.**

| LPD group | | | | | | | Matched control | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Participant | Age | Grade | Gender | Class type | Handedness | Additional details | Participant | Age | Grade | Gender |
| DV | 10:10 | 5 | Male | Regular | Right | Diagnosed with ADHD | EZ | 11:1 | 5 | Male |
| HN | 11:3 | 5 | Male | Small | Right | | YN | 11:5 | 5 | Male |
| SL | 9:11 | 4 | Female | Regular | Right | | ST | 9:9 | 4 | Female |
| SN | 11:2 | 5 | Male | Small | Right | Transient left hemiplegia in the beginning of 1st grade. Selective attention deficit | DD | 11:4 | 5 | Male |
| HA | 13:2 | 8 | Female | Learning disabilities school | Right | Diagnosed with ADHD | SR | 13:5 | 8 | Female |
| NS | 13:11 | 7 | Female | Regular | Right | Selective attention deficit | TH | 13:8 | 7 | Female |
| SP | 9:4 | 3 | Female | Small | Right | Selective attention deficit | GF | 9:5 | 3 | Female |
| RM | 9:6 | 3 | Male | Small | Right | Selective attention deficit | ER | 9:5 | 3 | Male |
| RI | 15:9 | 10 | Male | Small | Left | | MR | 15:7 | 10 | Male |
| AN | 9:9 | 4 | Female | Regular | Right | Diagnosed with ADHD | SN | 9:9 | 4 | Female |
| YS | 29:10 | – | Male | – | Left | | OF | 29:4 | – | Male |

task, but did not show significant indications of any other types of dyslexia. For a detailed description of their reading pattern, see Friedmann and Rahamim (2007).

The control group included 11 participants without reading or language disabilities, each matched to a participant in the LPD group in gender, age (up to 3 months difference from the matched LPD participant), and school grade.

2.1.1.2. Background information on word reading and establishment of letter position deficit. The participants had a significant deficit in reading words, manifested in migrations of letters within words. These migrations occurred predominantly in middle positions, in both vowels and consonants, and involving letters that serve as affixes as well as root letters. A summary of their reading performance, taken from Friedmann and Rahamim (2007), is brought in Table 2. The table shows the results of a word-reading task, in which single migratable words were presented for oral reading; a task of reading words in text, in which migratable words were incorporated within a story; a same–different decision task, in which pairs of words that differed in letter order were shown (the data given in Table 2 are for the 30 different-order pairs); a word definition task, in which migratable words were presented and the participants defined them; and a lexical decision task of migratable nonwords, in which the participants were shown a nonword created by changing the letter order of an existing words, and were asked to determine whether it is a word or a nonword.

These data indicated unequivocally that each of them had a letter position deficit in word reading. The comparison of the migration error rate of each LPD participant with that of the control group indicated that each participant had significantly more migration errors than the control group in at least three word-reading tasks (using Crawford and Howell's, 1998 significance *t*-test).

Our next step was to assess the ability of these individuals to read numbers, in order to directly compare between their reading of words and numbers. Words and numbers were compared using two tasks: reading aloud of words and numbers, and same–different decision of word pairs and

**Table 2 – Percentage of migration errors in various word-reading tasks.**

| Participant | Reading single words | Reading words in text | Same–different decision | Word definition | Lexical decision: migratable nonwords |
|---|---|---|---|---|---|
| DV | 14* | 6* | 93* | 16* | 19* |
| HN | 43* | 28* | 33* | 48* | 81* |
| SL | 16* | 11* | 10 | 12 | 11* |
| SN | 37* | 33* | 10 | 20* | 28* |
| HA | 28* | 8* | 20* | 56* | 47* |
| NS | 16* | 6* | 27* | 32* | 42* |
| SP | 39* | 21* | 67* | 44* | 75* |
| RM | 12* | 6* | 23* | 8 | 3 |
| RI | 28* | 7* | 10 | 24* | 17* |
| AN | 27* | 7* | 13 | 20* | 14* |
| YS | 15* | 3 | 33* | 16* | 31* |
| LPD average (SD) | 24.9* (11.1) | 12.5* (10.2) | 31* (26) | 26.9* (15.9) | 33.3* (25.6) |
| Control average (SD) | 1.9 (1.3) | 1.9 (1.1) | 3.1 (3.0) | 5.5 (6.0) | 4.3 (4.4) |

* Significantly poorer than the controls, $p < .05$.

number pairs that differ in the order of letters or digits. Because letter position errors stem from a deficit in the visual analyzer, if the visual analyzer is responsible for reading both words and numbers, we would expect position impairment in number reading as well, causing digit migrations within numbers.

2.1.1.3. PROCEDURE. Each participant was tested in a series of one hour sessions, in a quiet room. Words and numbers were presented on paper, in 18 pt. David font. Each stimulus was presented on a separate sheet without time limitation.

The number and types of errors of each participant in the LPD group in each task was compared to those of the control group using Crawford Howell's t-test (1998). The performance of the LPD and the control groups were compared using Mann–Whitney test. The comparisons between conditions at the group level were conducted using Wilcoxon Signed-Rank test. Comparisons between the performance of each participant and the matched control participant, and comparisons between the performance of each participant on two conditions were conducted using the chi-square test.

### 2.1.2. *Experiments comparing word and number reading*

2.1.2.1. EXPERIMENT 1: READING SINGLE MIGRATABLE WORDS AND NUMBERS

**2.1.2.1.1.** WORD READING. Friedmann and Gvion (2001) found that the letter position deficit is manifested most clearly in migratable words, i.e., words in which a migration results in another existing word. We therefore used only migratable words in this task. Examples (1) and (2) show migratable words that were used in the reading task, and their possible migration results (the examples show the Hebrew stimulus, orthographic transcription, phonological transcription, meaning).

(1) מאפרה-מרפאה (MAPRH-MRPAH, ma'afera-mirpa'a, ashtray-clinic)
(2) תריס-תירס (TRIS-TIRS, tris-tiras, window screen - corn)

Each participant read aloud 418 single migratable words in Hebrew; 362 of these words had a lexical potential for middle letter migration, 286 words had a potential for exterior letter migration (for some words, both migration of middle letters and migration of exterior letters could create existing words). The words were 3–7 letters long, with average length of 4.75 letters. All the words in the list were selected so that both the target word and its migratable counterpart were known to children in the youngest participants' age. The familiarity of the words was determined by 33 3rd and 5th graders with intact reading, who were asked to grade how familiar they were with the words, and circle the words they did not know.

**2.1.2.1.2.** NUMBER READING. The participants were also asked to read aloud numbers, presented in a separate list of 90 numbers. The numbers were read aloud as a whole number (rather than digit by digit). Thirty numbers were 4-digit long, 30 were 5-digit long, and 30 were 6-digit long. All the digits were used, the digit 0 appearing in 30 of the numbers, and no number included two adjacent identical digits.

**Table 3 – Percentages of letter migrations in words, and of digit migrations in numbers.**

| Participant | Migration errors in word reading | Migration errors in number reading | $\chi^2$ numbers versus words |
|---|---|---|---|
| DV | 13.6$^+$ | 2.2 | 8.93** |
| HN | 42.8$^+$ | 2.2 | 47.24*** |
| SL | 12.3$^+$ | 1.1 | 9.98** |
| SN | 36.6$^+$ | 2.2 | 37.78*** |
| HA | 28.2$^+$ | 2.2 | 26.21*** |
| NS | 15.8$^+$ | 2.2 | 11.24*** |
| SP | 39.2$^+$ | 0 | 48.80*** |
| RM | 12.4$^+$ | 0 | 13.27*** |
| RI | 27.5$^+$ | 6.7 | 15.34*** |
| AN | 26.6$^+$ | 3.3 | 21.21*** |
| YS | 14.6$^+$ | 12.2$^+$ | .24 |
| Control average (SD) | 1.9 (1.3) | 2.0 (2.0) | |

** $p < .01$, *** $p < .001$.
$^+$ Significantly more migrations than the control group, $p < .001$.

2.1.2.2. RESULTS

**2.1.2.2.1.** WORD READING. The results, shown in Table 3, indicated that all the individuals with LPD had a marked letter position deficit, which resulted in many migration errors within words. The average error rate amounted to a quarter of the words. For one of the participants, HN, the rate of letter migrations was as high as 43% of the words with middle letter migration potential.

Each of the LPD participants had significantly more migration errors than their matched control participant ($p < .001$ for each individual), and significantly more migration errors than the control group, $p < .0001$. On the group level too, the LPD group had significantly more migration errors than the control group, $z = 3.94$, $p < .001$.

**2.1.2.2.2.** NUMBER READING. The results, summarized in Table 3, show that although the LPD participants had a considerable deficit in letter position, all but one did not have a parallel deficit in digit position. All control participants, and 10 LPD participants, showed good number reading: they had between 0 and 6 digit migration errors. The 10 LPD participants performance was not different from that of the control group. YS, on the other hand, made significantly more errors than the control group, $t(10) = 4.81$, $p < .0001$.[4] As a group, the 10 other participants with LPD did not have more digit migration errors than the control group, $z = .26$, $p = .79$, nor did they produce more other errors in reading numbers, $z = .11$, $p = .91$.

As seen in Table 3, the direct comparison of migrations rates between word and number reading indicated that all the LPD participants except YS had significantly more migration

[4] Because YS and his matched control were considerably older than the rest of the participants, another option, which also makes sense, was to compare YS only to his control, and each of the other LPD participants to the rest of the control group. This comparison is even more impressive: although YS made **more** errors than the other LPD participants, his matched control made **fewer** errors than the other controls.

errors in reading words than in reading numbers ($p < .01$).[5] YS had a similar rate of migration errors in words and numbers.

2.1.2.3. Experiment 2: same–different decision in words and numbers. Another task we used to assess word and number reading was a same–different decision task, which assesses reading in a way that does not require oral output.

*2.1.2.3.1. Word task.* The participants were presented with 90 word pairs of three types: 30 pairs of identical words with potential for a lexical middle migration (חובשים-חובשים), 30 pairs of identical words without potential for a lexical middle letter migration (זקנים-זקנים), and 30 pairs of migratable words that differed in letter order (טלפון-טפלון). The words included 4–6 letters. (The test included 30 additional pairs of words that differed in the identity of one letter, which were not problematic for the LPD participants, and will not be discussed in the current article.) The words in each pair were presented side by side, as in the example above, and the participants were asked to judge whether the words in each pair were the same.

*2.1.2.3.2. Number task.* The participants were presented with 90 number pairs: 30 were 4-digit long, 30 were 5-digits long, and 30 were 6-digits long. Half of the pairs in each length were identical, and half differed in the order of middle digits. The numbers were presented without comma separators. The participants were asked to judge whether the numbers were the same. NS gave up on this task, so only the performance of the other 10 participants is analyzed.

2.1.2.4. Results

*2.1.2.4.1. Words.* As can be seen in Table 4, the LPD group had significantly more errors than the control group in this task, $z = 2.76$, $p = .003$. Nine of the participants with LPD had more errors than their matched controls, a difference that was significant for seven of them. Seven of the participants performed significantly poorer than the control group. The average error rate for pairs that differed in letter order was 31%. The average error rate for identical pairs was low, 4% for identical migratable pairs, and 1.7% for identical non-migratable pairs.

*2.1.2.4.2. Numbers.* Unlike the word task, all LPD participants but two, SP and YS, performed well on the numbers task. Like in Experiment 1, the LPD group did not differ from the control group, $z = .92$, $p = .36$. Only YS performed significantly poorer than the control group, and had significantly more errors than his matched control. As in the reading aloud task, YS showed letter and digit-position deficits, failing to identify both letter order and digit order differences. The average error rate was 4.7% for pairs that differed in digit order, and 3.1% for the pairs of identical numbers (excluding YS, who clearly had a problem in reading numbers, the average error rates were 3.7% and 1.5%, respectively).

Like in Experiment 1, a group-level comparison of error rates on different-order pairs between numbers and words showed that the participants with LPD made significantly more errors in detecting order difference in word pairs than in number pairs, $T = 0$, $p = .002$.

2.1.2.5. Summary. The results show that 10 of the participants had a considerable letter position deficit in reading words, which caused migration errors in reading, but had no position deficit in reading numbers. Their reading of numbers was similar to that of the control group. Only one participant with LPD, YS, had migrations in both numbers and words, both in reading aloud and in same–different decision. These results

**Table 4 – Same–different decision: percentage of errors in words and numbers.**

| LPD participants | Words ($n = 90$) | Numbers ($n = 90$) |
|---|---|---|
| DV | 31* | 2 |
| HN | 13* | 6 |
| SL | 3 | 0 |
| SN | 4 | 0 |
| HA | 10* | 0 |
| NS | 9* | – |
| SP | 24* | 11 |
| RM | 11* | 0 |
| RI | 4 | 2 |
| AN | 4 | 0 |
| YS | 19* | 14* |
| Control average (SD) | 3.4 (3.3) | 4.3 (3.1) |

* Significantly more migrations than the matched control participant, $p < .05$.

[5] A reviewer suggested to us that the higher error rate in words is a results of frequency: if the word presented is less frequent than its migrated counterpart, the higher frequency of the non-presented word may cause the reading modules to prefer it over the presented word, whereas such consideration cannot trigger migrations of numbers. Indeed, a frequency effect does exist in letter position dyslexia, and less frequent words have a higher chance to be replaced by their frequent counterpart than the other way around, as we reported in Friedmann and Rahamim (2007). However, although frequency effect exists in LPD, we still do not view it as the reason for migrations, but as a factor that modulates the response selection when position under-specification occurs. When middle letter position is under-specified, the orthographic input lexicon usually access first the more frequent word among the migratable alternatives that match the underspecified input (Friedmann and Rahamim, 2007). Thus, although frequency affect LPD, it is not the reason for the difference between words and numbers, for several reasons:
i. If frequency were the sole reason for migrations, then migration errors should have occurred only from less frequent to more frequent words, but not from frequent to infrequent and not in equi-frequency word pairs. However, our participants did have migration errors in which they read a frequent word as an infrequent one (Friedmann and Rahamim, 2007, pp. 214–215).
ii. Even if we look only at the errors in the less common direction, from frequent to infrequent, the average rate of migration errors made by the 10 participants (YS excluded) was 12%, a rate that is significantly higher than their average of 2.2% migrations in number reading ($T = 6.5$, $p = .01$). The frequency hypothesis cannot account for this difference.
iii. The frequency hypothesis does not explain why EY (who is presented later, in part B of the article) and YS did have migration errors in numbers (in fact, they had more migrations in numbers than in words).

form a clear dissociation between the reading of words and numbers. All participants had an impairment in one of the modules of the visual analyzer, an impairment that made them read words with migration errors. The dissociation that 10 of them showed between words and numbers indicates that this module is not used in number reading, and that the visual analyzer – or at least its part that is responsible for identifying the position of letters within the word – is **orthography-specific**.

### 2.2. *Part B: characteristics of number and word reading – YS and EY*

The first part of the study showed a very clear dissociation between word and number reading for 10 of the participants: their word reading was impaired but their number reading was intact. The aim of the second part of the study was to localize the source of the functional deficit in words and numbers and to closely assess the reading pattern of individuals who are impaired in both types of stimuli, by comparing the patterns of errors they make in word reading and in number reading. If different error patterns emerge, this will provide further reason to believe that words and numbers are processed differently. Such differences might also help to further understand the mechanism (or mechanisms) of word and number reading.

#### 2.2.1. *Method*

2.2.1.1. Participants. YS was the only participant among the 11 LPD participants in Experiments 1 and 2 who had migration errors both in reading words and in reading numbers. In this part of the study we further examined his pattern of reading of words and numbers. As this part of the study was conducted a while after the previous part, his age was 33 at the time of examination. We also included another participant, EY, a 34 year-old woman who studied toward a Ph.D. in mathematical science. Our initial testing indicated that she had a significant letter position deficit in reading of words and nonwords, and digit-position errors in number reading. She reported that the Ph.D. studies were much easier for her than the BA level courses in mathematics, because the BA level courses required more reading of numbers.

2.2.1.2. Procedure. Each participant was tested in a series of one hour sessions, in a quiet room. Long tasks were broken down into parts so that each single task took less than 10 min. The stimuli were presented on a 15″ computer monitor in 26 pt. David font. Each stimulus was presented for 400 msec. The participants controlled the onset of each stimulus with the mouse, and each list of stimuli began with 3 training stimuli to let the participants get used to the software. The exposure time was limited in order to make sure that enough errors were produced: when EY read from paper with unlimited exposure, she used various reading strategies that made her reading nearly errorless (and very slow, especially for migratable words). YS showed similar rate of migrations in limited and unlimited exposure, so we used limited exposure to equate the presentation conditions of the two participants.

2.2.1.3. Initial assessment of word reading. Both participants had a relatively pure letter position dyslexia. For the initial assessment we used the TILTAN test battery (Friedmann and Gvion, 2003). This test showed that both participants had within-word migration errors in reading of words (EY: 23%; YS: 21%) and nonwords (13% for both participants). None of them had any other type of errors in word or nonword reading, except one omission error of YS.

#### 2.2.2. *Experiment 3: reading assessment of numbers and words*

2.2.2.1. Word reading task. Each participant read aloud 326 single migratable words in Hebrew. The words were 3–7 letters long, with an average length of 5.0 letters (SD = .87). The words were constructed so that 280 words had potential for a lexical middle letter migration, of either adjacent letters (233 words) or nonadjacent letters (84 words); and 236 words had a potential for exterior letter migration (many words had potential for more than one error type). We chose migratable words because they are more similar to numbers than non-migratable words in an important way: digit migration in a number results in another number. Letter migration can result in another existing word only in migratable words, but not in non-migratable words.

2.2.2.2. Number reading task. Each participant read aloud 212 Arabic numerals. The numbers did not include the digits 0 and 1, and all the digits in each number were different from each other.[6] One list included 132 numbers in random order: 50 3-digit numbers, 42 4-digit numbers, and 40 5-digit numbers. Another list included 80 6-digit numbers. The numbers were presented without a comma separator between the thousands and the hundreds digits.

2.2.2.3. Results. In *word reading*, letter migration within words was the predominant error type for both EY and YS. EY had migration errors on 17.2% of the words (which accounted for 95% of her errors), and YS had migration errors on 7.1% of the words.[7]

As for *number reading*, the results of Experiment 1 were essentially replicated: both participants had high rate of migrations – EY had 31.6% digit migrations and YS had 32.5% (their general error rates were 58% and 60% respectively, see Appendix A for details and discussion of the non-migration errors). They both made more errors in reading numbers than in reading words, and the same was true when counting the migration errors alone. The difference in error rates between

[6] The reason for excluding 0 and 1 was that we discovered that the rate of migration errors is dramatically reduced when the number contains the digits 0 or 1. This is described in detail in Dotan and Friedmann (in press). See Cohen and Dehaene (1991) for a discussion of the special status of 0 in Arabic numerals reading.

[7] YS's 10 other errors included 9 letter additions, 4 of which were *copy errors*, in which the added letter existed somewhere else in the target word. It is possible that the copy errors were migrations (in which a letter moves to another place *and* remains in its original position), but we chose the more conservative way and counted them separately.

words and numbers (both for the LPD participants and for the controls, described below) might result from the fact that in numbers, each possible migration leads to a valid number, whereas in words, lexicality and frequency considerations reduce the likelihood for certain possible migrations.

In order to make sure that the migration errors indeed originated in the participants' dyslexia rather than in the limited exposure, we compared their reading in Experiment 3 to the reading of 10 control participants in the same conditions of limited exposure. The ages of the control participants were similar to those of YS and EY, 25–35 years ($M = 30.6$, $SD = 2.7$).

The control participants read the same 326 words and 82 of the Arabic numbers (half with 4 and half with 5 digits), using the same exposure durations (of 400 msec). Table 5 compares the migration errors made by EY, YS, and the control participants in reading these 326 words and 82 numbers.

The performance of the control participants was very good in both types of tasks (above 96% correct), although they read words better than numbers. Altogether, they read 3260 words, in which they had only four errors (0.1%), with a single migration error. They also read 820 numbers and had 34 errors (4%), 10 of which were migrations. Because the control group's performance was at ceiling, with very small variance, it was impossible to use *t*-tests or dissociation analyses that are based on them to compare EY and YS's performance to the control group (Crawford and Howell, 1998; Crawford and Garthwaite, 2007. See Willmes, 1990 regarding the difficulty in using ceiling level scores of healthy individuals). A Fisher's exact *p* showed that both EY and YS had significantly more errors than the control participants in both words and numbers.

Thus, the results indicated that limiting the exposure duration to 400 msec did not result in a significant rate of letter or digit migrations for the control participants, and that the migration errors that EY and YS made in limited exposure reflect a genuine difficulty in position encoding. Results from another study that assessed normal reading with an even shorter exposure times (200–250 msec) indicated that even in shorter exposure times, Hebrew-readers do not produce errors of letter position within words (whereas they do produce letter identity errors and migrations between words, Shetreet and Friedmann, in press).

### 2.2.3. *Migration errors in words: the locus of the impairment*

The previous studies of acquired and developmental letter position dyslexia for words indicate that the deficit is located in input rather than output modules. This was assessed using production tasks that do not involve written input, such as repetition tasks and analysis of spontaneous word production, which showed intact production, without migrations (Friedmann and Gvion, 2001; Friedmann and Rahamim, 2007). It was also assessed using tasks of reading without spoken output, which showed migrations: comprehension of migratable words was affected in the same way as reading aloud, namely, participants with LPD made errors in comprehension tasks indicating they understood words as their migrated counterpart. They also tended to judge nonwords as words in a lexical decision task if a middle letter transposition within the nonword created an existing word (such as "wrod"). The conclusion from these findings was that letter position errors in these patients resulted from an impairment in the input stages of the reading process, prior to the access to the orthographic input lexicon and semantics, and more specifically – in the position-identification function of the visual analyzer. In order to assess whether this is also the case for EY and YS, we tested them in several reading tasks that do not involve spoken output: same–different decision, word definition, and lexical decision. We also tested them in a word repetition task, which involves word production without reading.

The *same–different decision task* was already described in part A of this study (see Section 2.1.2.3, Table 4). It indicated that YS had many errors in the word pairs that differed in the order of letters, even when he did not read the words aloud. This finding is consistent with the assumption of an input module impairment.

2.2.3.1. Experiment 4: word definition. Each participant was requested to define 27 words with a potential for middle letter migration, without reading them aloud. The length of the words was between 4 and 7 letters, with an average length of 5 letters. A migration error in this task will make the participant comprehend the transposed counterpart of the migratable target word, and hence provide a wrong definition. For example, if the participant sees the word *beard* and defines it as "something you eat with butter", we can conclude that a migration error occurred in a stage prior to the comprehension of the target word, and that he actually understood it as *bread*. The participants' definitions were scored by three independent judges. Inter-judge agreement was over 95% for EY and 100% for YS.

***2.2.3.1.1.*** **Results.** Both participants had a high rate of migration errors in the migratable word definition task – EY defined 13 words (48%) as their migration counterpart, and YS did so in 5 words (19%). EY also had one non-migration error, and YS had two. Evidently, the letter position dyslexia affects both reading aloud and comprehension, a finding indicating an input, rather than output, origin of the deficit.

2.2.3.2. Experiment 5: lexical decision. The participants were shown strings of letters, some of which were real words and some were nonwords. They were asked to say, for each letter string, whether it was an existing word ("word") or not ("no"). There were two types of nonwords in this task: *migratable* nonwords, which differed from an existing word only by the order of middle letters, and *non-migratable* nonwords, which were words in which one or two letters were substituted, and

**Table 5 – Percentage of migration errors in word and number reading, and comparison to the control group.**

| | Words | Numbers |
|---|---|---|
| EY | 17.2%+ | 37.8%+ |
| YS | 7.1%+ | 32.9%+ |
| Control average (SD) | 0.03% (0.1%) | 1.2% (2.9%) |

+ Significantly more errors than the control group, Fisher's $p < .001$.

did not have potential for a lexical migration. A letter position deficit at the visual input is expected to affect the recognition of migratable nonwords, which will be judged as words, but not of non-migratable nonwords.

EY judged 66 letter strings: 21 words, 22 migratable nonwords, and 23 non-migratable nonwords. YS judged 125 letter strings: 59 words, 43 migratable nonwords, and 23 non-migratable nonwords. Their performance was compared with that of 10 control participants, aged 26–37 ($M = 31.5$, $SD = 3.3$), who read the same strings of letters that EY did.

**2.2.3.2.1. Results.** EY accepted 15 migratable nonwords as words (68%), whereas she had only one error in non-migratable nonwords and one error in words. She had significantly more errors in the migratable nonwords than in the non-migratable nonwords (Fisher's $p < .001$). YS had 13 errors, all of which were in the migratable nonwords (30%), again, significantly more than in the non-migratable nonwords (Fisher's $p = .002$). The control participants had an average of 1.1 errors in migratable nonwords (3.7%, $SD = 4.2\%$), performance which was close to ceiling. Both participants had significantly more errors than the controls on the migratable nonwords (Fisher's $p < .001$). Again, these findings are consistent with an input module impairment.

2.2.3.3. Experiment 6: word repetition. To assess whether migrations also occur in the participants' output when the task involves no word reading, the participants were asked to repeat 98 words. The task included 48 migratable words, 25 non-migratable words, and 25 nonwords. Both participants performed virtually flawlessly: EY had one substitution error, and YS had no repetition errors at all. The good performance in this task indicates that the participants' migration errors did not originate in the production modules or in working memory.

2.2.3.4. Interim summary: the source of migration errors in words. The tasks of written input without spoken production (same–different decision, word definition, and lexical decision) indicated that the letter position dyslexia of both participants affects word identification and comprehension even when no production is involved. The production task without written input (repetition) indicated that production is intact when it does not involve reading. Their spontaneous speech was also completely normal, without phoneme order errors. Taken together, these results are in line with previous studies about letter position dyslexia and clearly indicate that their dyslexia is caused by a deficit in the input modules.

#### 2.2.4. *Migration errors in numbers: the locus of the impairment*

In the previous section we showed that the letter position dyslexia EY and YS had in word reading was caused by a deficit in the input module. The current section assesses the locus of impairment that caused their migration errors in number reading. Do digit migrations originate, like letter migrations, in an input module deficit?

Various theoretical models were suggested for number processing, and each model describes different modules and processes involved in number processing (Dehaene, 1992; McCloskey, 1992; Cohen et al., 1994; Cipolotti and Butterworth, 1995). There are, however, several assumptions shared by all of these models: obviously they all acknowledge the fact that number reading involves digit input and verbal production of number words, although they describe differently the modules responsible for carrying out these processes. All models agree that there exists a semantic Arabic-to-verbal transcoding route converting input digits, through semantics, to the production of number words (input → semantics → production). Researchers disagree about the existence of a direct asemantic transcoding route (input → production): Dehaene (1992) claimed that such a route exists, and even views it as the main Arabic-to-verbal transcoding route, whereas McCloskey (1992) claimed that such a route does not exist.

We assessed possible impairment locations that can cause digit migrations: the input module and the production module. We also considered the possibility that a direct Arabic-to-verbal transcoding route does exist, and that the deficit that caused migrations originates in this route. If we discover that this is the case, this could be used as evidence for the existence of a direct Arabic-to-verbal transcoding route. If the deficit is elsewhere, this will not bear on the existence of this route.

Several studies of number reading reported cases which can be ascribed to a specific impairment in any of these alternative locations of impairment – in the input modules (Noel and Seron, 1993), in the production modules (Temple, 1989; Marangolo et al., 2004; Dotan and Friedmann, 2007), or in the direct transcoding route of written Arabic numerals to verbal numbers (Cohen et al., 1994; Cipolotti, 1995; Cipolotti and Butterworth, 1995; Cipolotti et al., 1995; Cohen and Dehaene, 2000).

In order to localize the origins of EY's and YS's impaired number reading, we used several tasks: to assess their input modules, we used *same–different decision* and *sequence identification* tasks. In the *same–different decision* task, the participants were presented with pairs of numbers, and were asked to decide whether the numbers in each pair were identical. In this task the participants were not requested to produce any number orally, and were not requested to transcode Arabic numerals into number words. Another task, which was also aimed at assessing the input modules, and which did not require production or transcoding, was *sequence identification*: the participants were shown a number and were required to decide whether its digits form a consecutive sequence or not. These two tasks tap the input modules. In the *number repetition* task, the participants were requested to repeat numbers that the experimenter said. This task involves the output modules, and does not involve digital visual input or Arabic-to-verbal transcoding. Thus, it can be used to assess the number production module. A failure in the same–different decision and sequence identification tasks, together with unimpaired production in the repetition task would indicate that the deficit stems from an impairment at the visual input modules.

Finally, we used the *simple addition* task, an extended version of the *what comes next?* task (Cipolotti et al., 1995). The participants saw a number, and were asked to add to it either 1 or 10, saying aloud only the result. This task forces the participants to read via the semantic route, so we expect them

Table 6 – Percentage of errors in the same–different decision task.

| | EY | YS | Controls (SD) |
|---|---|---|---|
| Migration pairs | 63%** | 21%** | 1.9% (2.5%) |
| Substitution pairs | 0% | 8%* | 0.4% (.6%) |
| Identical pairs | 0% | 9%* | 0.1% (.4%) |
| Migration versus substitution | Fisher's $p < .001$ | $\chi^2 = 5.3$, $p = .02$ | |
| Migration versus identical | Fisher's $p < .001$ | $\chi^2 = 5.7$, $p = .02$ | |

* Significantly more errors than the control participants average, Fisher's $p < .003$.
** Fisher's $p < .02$.

to perform well if their impairment is in Arabic-to-verbal transcoding. Furthermore, impairment in the input or in the production modules should lead to different error patterns in this task.

2.2.4.1. Experiment 7: same–different decision. The same–different decision is an input task which does not involve any number production: the participants were only required to decide whether two numbers are identical or not. Thus, it can be performed solely using the input and the processing modules, and without the output modules or Arabic-to-verbal transcoding. The task included 270 pairs of 4-digit numbers. The numbers in each pair appeared together in the middle of the screen, presented horizontally, for 2300 msec. To decide whether the two numbers were identical, the participants used the mouse to choose "same" or "different" on the screen. They could answer while the pairs appeared on screen or after they disappeared. Of the 270 pairs, 120 were identical numbers (*identical pairs*), 75 differed in the digit order of two adjacent digits (*migration pairs*), and 75 differed in a single digit (*substitution pairs*). Of the 75 substitution pairs, the digit change was in the thousands digit in 10 pairs, in the hundreds digit in 15 pairs, and in the tens and units digits in 25 pairs each. Of the 75 migration pairs, the difference was in the two leftmost digits in 15 pairs, in the middle digits in 20 pairs, and in the rightmost digits in 40 pairs. The performance of EY and YS was compared with that of 10 control participants aged 17–35 ($M = 28.8$, $SD = 4.10$).

**2.2.4.1.1.** ***Results.*** Table 6 shows the percentage of errors in the various types of pairs (see Table 13 for results according to position). EY had errors only in the migration pairs; she performed flawlessly in the identical and substitution pairs. YS had errors in all types of pairs, but both participants had significantly more errors in the migration pairs compared with the other pairs.

The control participants performed at ceiling in this task, with more than 98% correct answers for all types of pairs, and very small variance. A Fisher's exact test showed that EY performed significantly poorer than the controls in the migration pairs ($p < .001$), whereas in the other types of pairs she actually performed better than them. YS performed significantly worse than the control participants in all types of pairs, but the difference was most striking in the migration pairs.

As this task involved only the input modules, these results further indicate that the migration errors originate in an input module impairment.

2.2.4.2. Experiment 8: sequence identification. Another task we used to test the input modules as a possible source of the migration errors was the sequence identification task. This task, too, is an input task that requires neither production nor Arabic-to-verbal number transcoding (although it probably involves access to a semantic module which knows the order of numbers). It was also designed to minimize the dependency on working memory: the same–different decision, although a comprehension task, required the participant to store two numbers in memory until they are compared. The sequence identification task required the participants to remember only 4 digits, well within their span, thereby focusing on the input modules.

The participants were shown 300 4-digit numbers, consisting of the digits 2–9. Each number was presented for 400 msec, and the participants had to decide whether this number forms a consecutive sequence or not (for example, 4567 is a consecutive sequence, but 4657 and 4568 are not). They used the mouse to choose "yes" or "no" on the screen.

Table 7 – Percentage of errors in the sequence identification task.

| | EY | YS | Controls (SD) |
|---|---|---|---|
| Migration stimuli | 36%* | 12%* | 1.3% (1.3%) |
| Substitution stimuli | 4% | 0% | 0.1% (0.4%) |
| Consecutive stimuli | 1% | 3% | 0.9% (1%) |
| Migration versus substitution | Fisher's $p < .001$ | Fisher's $p = .002$ | |
| Migration versus consecutive | Fisher's $p < .001$ | $\chi^2 = 6.4$, $p = .01$ | |

* Significantly more errors than the average of control participants, Fisher's $p < .01$.

Of the 300 numbers, 150 were consecutive sequences (e.g., 4567, *consecutive stimuli*), 75 were sequences that were created by substituting one digit in a consecutive number (e.g., 4597, 2567, *substitution stimuli*), and 75 were sequences that were created by transposing two adjacent digits in a consecutive number (e.g., 4657, *migration stimuli*). The distribution of the substituted or migrated digits across positions in the sequence was like in the same–different decision task (Experiment 7). The performance of EY and YS was compared with that of 10 control participants, aged 22–40 (M = 29.2, SD = 5.6).

*2.2.4.2.1.* Results. Table 7 shows that both participants had more errors in the migration stimuli than in the substitution and consecutive stimuli (see Table 13 for results according to position). In this task too, the control participants performed at ceiling. EY and YS performed significantly poorer than the controls in the migration stimuli, and performed well in the other stimuli. These results again indicate that the migration errors originate in an impaired input module.

2.2.4.3. Experiment 9: number repetition. In order to test the memory and production abilities of EY and YS, they were orally presented with 82 numbers, taken from the list of numbers that they read in Experiment 3 (these were the same numbers read by the control participants in Experiment 3). In one session they repeated 40 five-digit numbers and in another session they repeated 42 four-digit numbers. Each number was read aloud by the experimenter, and the participant repeated it.

*2.2.4.3.1.* Results. Both participants had a low rate of migrations in this task, which was not significantly higher than zero (EY: 1%, Fisher's $p = .5$; YS: 5%, Fisher's $p = .06$). All migrations were in 5-digit numbers. There were significantly less migration errors in this task than in the number reading task (Fisher's $p < .001$ for both participants), even when comparing only the 5-digit numbers (EY: Fisher's $p < .001$; YS: Fisher's $p = .01$).[8] These findings suggest that migrations in number reading are not caused by an impairment in the production stage.

2.2.4.4. Experiment 10: simple addition. Another task aimed at the localization of the number reading deficit of the participants was a simple addition task. The participants were presented with 140 numbers which were 4- and 5-digit long and consisted of the digits 2–8. They were requested to add either 1 or 10 to each number they saw, and say the result aloud. The semantic nature of this task encourages the participants to use the *input* → *semantics* → *production* route rather than a direct asemantic transcoding route.

Different loci of impairment are expected to be reflected in different patterns of migration errors in this task. We will illustrate this using the example 3268 + 1, in the case that last two digits were transposed. If the migration error occurred in the input modules (*input migration*), the input to semantic processing will be 3286 + 1, and the participant will say 3287. On the other hand, if the migration error occurred in the output module (*production migration*), the participant will process correctly the exercise 3268 + 1 and reach the correct result, 3269, but will then transpose the digits and say 3296. Transpositions in digits other than the tens and units (such as saying 2369) are ambiguous and are not indicative about the source of the migration (*ambiguous migrations*).[9] Our analysis compared only the input versus production migrations, and excluded the ambiguous migrations.

**Table 8 – Simple-addition task: percentage of migration errors that involve the digit to which 1 or 10 is added.**

| Error type | EY | YS |
|---|---|---|
| Input migrations | 11.4% | 5.7% |
| Production migrations | .7% | .7% |
| Ambiguous migrations | 7.1% | 9.3% |
| All migrations | 19.3% | 15.7% |

Each number in the list was displayed in the following way: first, a cue of either "+1" or "+10" appeared on the computer screen for 1 sec. Then the cue disappeared, and after a delay of 800 msec the target number appeared for 400 msec. The digit 9 was not used in this experiment, so carry procedure was never required, and the participants were informed about this before the experiment began.

*2.2.4.4.1.* Results. Both participants said that this was definitely the most difficult task they did during the study. They both felt that they performed very poorly on this task compared with the standard reading task, although their total error rate was similar to the reading task (EY: 49.3%; YS: 56.4%).

The participants made migration errors in this task (EY: 19.3%; YS: 15.7%), as well as operation errors (EY: 7.1%; YS: 7.9%) and missing-digit errors (EY: 32.1%; YS: 13.6%; see Appendix A for a discussion of miss errors in reading).

The high rate of migration errors in a task that clearly does not use the direct Arabic-to-verbal transcoding route suggests that the impairment causing the migrations is not specific to the direct route. Table 8 shows that most of the migrations were either input or ambiguous migrations. Both participants had significantly more input than production migrations (EY: Fisher's $p < .001$; YS: Fisher's $p = .02$). These results, like the results of the previous tasks, indicate that the migration errors originate in the input modules.

2.2.4.5. Interim summary: the source of migration errors in numbers. In this section, we assessed which of several alternative loci of impairment causes the migration errors in number reading: the input modules, the production modules, or a specific Arabic-to-verbal transcoding process.

[8] Even those few migration errors that YS had in this task were different from the migrations in the reading task: 3 out of his 4 migrations involved the leftmost digit of the target number, whereas in the reading task, as we will see later, migrations tended to occur on the rightmost digits.

[9] Another type of error that is not indicative with respect to the origin of the migrations, is the *operation error* – adding 1 instead of 10 or vice versa (or adding 11). In the case of 3268 + 1, an operation error will cause the participant to calculate 3268 + 10 and answer 3278. These errors were also categorized as ambiguous.

The findings indicated that migration errors are caused by an impairment in the input modules. Both participants had migration errors in the same–different decision task and in the sequence identification task. Because these two tasks involve neither production nor direct Arabic-to-verbal transcoding, these two alternatives are ruled out as the source of migration errors. Indeed, the same–different decision task relies on working memory more heavily than the other tasks in this study, but migration errors occurred also in the sequence identification task, which does not require much memory resources – so the working memory deficit cannot account for the migration errors.

The number repetition task provided further evidence for input module impairment. This task uses working memory as well as the production modules, and the absence of migration errors in it indicates that these two modules are not the source of such errors in number reading. Finally, the participants' error pattern in the simple addition task is consistent with the assumption that migration errors are caused by an impairment in the input modules rather than in the production modules.

#### 2.2.5. *Conclusions from non-migration errors in number processing*

So far, we have discussed only the migration errors the participants had in the various tasks. Indeed, in the word processing tasks, almost all their errors were migrations; but in the number processing tasks, they made other errors as well. Most of these other errors were either substitution of one digit by another, or *miss* errors – cases in which the participants were not sure about one or more digits, although they were aware of their existence (for a detailed analysis of these errors, see Appendix A). We refer to both substitution and miss errors as *digit identity* errors, because they both reflect a situation in which the participant lost the identity of one or more digits in the number. Based on several findings, we concluded that the identity errors do not originate in an input module deficit, but probably in the participants' reduced working memory. These findings are detailed in Appendix A (as they do not speak directly to the main research question regarding migrations). However, we do describe here two of these findings that are also relevant for our understanding of migration errors.

The first finding is the type of tasks in which each error appeared: as Table 9 shows, migration errors occurred in the number reading task, but not in the number repetition task, as expected from an input module deficit. Identity errors, however, occurred in both tasks, suggesting that they originate in the production system.[10] The same 82 numbers were used in the number repetition task and in the number reading task, so Table 9 shows a comparison between the reading and repetition of the same numbers.

**Table 9 – Rate of errors of various types in reading and repeating the same numbers.**

| | Migrations | | Identity | |
|---|---|---|---|---|
| | EY | YS | EY | YS |
| Number reading | 38% | 33% | 21% | 37% |
| Number repetition | 1% | 5% | 12% | 18% |

Interesting conclusions can also be drawn from the analysis of *mixed errors* in the number reading task – cases in which the participant transposed two digits *and* had an identity error in one of them. Mixed errors included *shift-and-miss* errors, in which one digit changed position, and the participant did not know what the other digit was (e.g., 734 → *seven hundred and forty something*); and *shift-and-substitution* errors, in which one digit changed position, and a new digit, which did not appear in the original number, took its place (e.g., 734 → 748).

The mixed errors can give us a clue regarding which type of error occurs first: migration errors or identity errors, and hence inform us about the relative location of the origins of these errors. The analysis we performed on these errors relies on the fact that identity errors tend to occur on the two rightmost digits (units and tens) more frequently than in other locations: EY had 10 times more identity errors in the two rightmost (units and tens) digits than in other digits (38% *vs* 4%, respectively, $\chi^2 = 116$, $p < .001$). YS had 13 times more tens and units errors (43% *vs* 3.3%, respectively, $\chi^2 = 239$, $p < .001$).

To define whether a mixed error was *migrate-then-forget* or *forget-then-migrate* error, we used the assumption that identity errors occur primarily in the tens and units digits. For example, reading 12345 as 12547 was coded as a *migrate-then-forget* error, because the sequence of errors 12345 → 1254**3** → 1254**7** was more likely than 12**3**45 → 12**7**45 → 12547, given that identity errors are more likely to occur in the units digit than in the hundreds digit. In the same way, reading 12345 as 12743 was categorized as a *forget-then-migrate error*. A similar line of argumentation can be applied to mixed migration and miss errors, in which the identity of one of the transposed digits was completely lost.

Such an analysis is valid only when there is a very big difference in the probability for an identity error between the two transposed positions. Thus, we analyzed only numbers with shift-and-miss or shift-and-substitution errors in which one of the transposed digits was the units or tens, and the other transposed digit was in another position (hundreds or leftwards). The results of this analysis were that EY had 7 such mixed errors, all of which were *migrate-then-forget* errors. YS had 36 mixed errors, 34 of them were *migrate-then-forget* errors. Thus, for both participants the majority of errors were of the *migrate-then-forget* type. A statistical analysis using binomial distribution, carried out on the unambiguous cases only, revealed that this difference was significant for YS ($p < .001$), and marginally significant for EY ($p = .06$).

These results support the *migrate-then-forget* hypothesis, hence indicating that identity errors happen at a later point in time than migration errors – i.e., either at a later stage within the input module, or after it. This makes perfect sense if indeed migration errors originate in the input stages, and identity errors in a later stage that involves working memory.

[10] Although there were almost no identity errors in the comprehension tasks (same–different decision and sequence identification), this finding cannot be used in this context because the comprehension tasks included only 4-digit numbers, in which the rate of identity errors was very low in the other tasks as well.

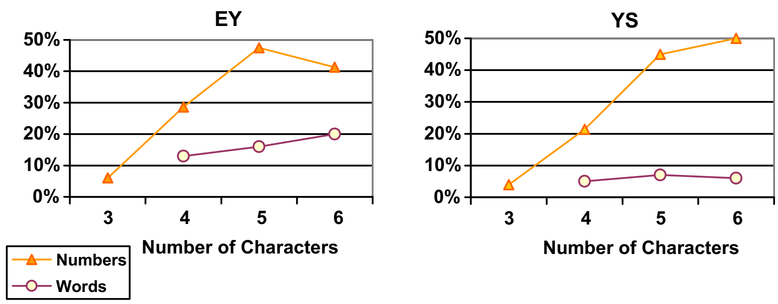


**Fig. 1 – Migration errors by stimulus length in word and number reading.**

It also provides further support to the conclusion that the deficit causing migrations is in an early stage in the reading process.

Attributing identity errors to a working memory limitation has an impact on our understanding of the relation between words and numbers. EY and YS do not have visual dyslexia – as they do not have identity errors in reading words. They do have such errors in reading numbers. It could have been claimed that this is a dissociation between word and number reading, and that the visual analyzer of EY and YS succeeded identifying correctly letters but not digits. The account we just gave for identity errors, together with the findings detailed in Appendix A, suggest that the identity errors in numbers do *not* originate in the visual analyzer, but rather at a later stage, and therefore this difference in the pattern of errors between words and numbers cannot be taken as evidence for different peripheral processing of words and numbers.

### 2.2.6. *How does the visual analyzer process words and numbers?*

The word and number reading tasks (Experiment 3) showed that both EY and YS make migration errors in both word and number reading. We showed that the source of migration errors in number reading is an impairment in the input modules, just like in word reading. The question now is whether the input modules process words and numbers in the same manner. To answer this question, we focused on analyzing the effect of length on reading words and numbers, the effect of adjacency of the transposed letters and digits, and the positions of the transposed letters and digits.

2.2.6.1. The effect of length on word and number reading. To learn about the processes of word and number reading, we assessed length effect in the two types of stimuli. The results of this analysis are shown in Fig. 1.

The analysis of the effect of length on migration errors in words was carried out on 310 words of 4–6 letters, by calculating point biserial coefficient.[11] No length effect was found for word reading (EY: $r = .07$, $p = .1$; YS: $r = .02$, $p = .4$). Conversely, the analysis of number reading showed a significant length effect for both participants (EY: $r = .29$, $p < .001$; YS: $r = .4$, $p < .001$). Table 10 presents a detailed analysis of the length effect, showing that it occurs between numbers of subsequent lengths, except the 6-digit numbers. However, the migration error rate in 6-digit numbers cannot be taken as reliable, due to the high rate of other errors, which may have masked the migration errors (in fact, nearly all 6-digit numbers were read with missing digits; see Appendix A for a discussion of these errors).

The existence of length effect on migration errors in numbers but not in words suggests a difference between the visual analysis of words and that of numbers. As we will see next, this was not the only difference.

2.2.6.2. Adjacency of the transposed letters and digits in the migration errors. In an analysis of the position of errors in word reading, Friedmann and Rahamim (2007) showed that migration errors in words occurred in both adjacent and nonadjacent letters, although some of their participants had significantly more migrations in adjacent than in nonadjacent letters. We compared the rate of adjacent-to-nonadjacent migrations in words and numbers to test whether this pattern is valid for number reading as well. We excluded the 3- and 6-digit numbers from this analysis: the 3-digit numbers were excluded because EY and YS made no migration errors in these numbers (and because 3-letter words were not included). The 6-digit numbers were excluded because both participants had miss errors in nearly all of these numbers, which would render the adjacent–nonadjacent analysis unreliable.

To enlarge the sample in YS's adjacency analysis, we added to the 326 words he read in Experiment 3, 293 migratable words he read aloud in other tests. Thus, the analysis is based

**Table 10 – The effect of length on migration errors in the number reading task (Experiment 3).**

| | EY | YS |
|---|---|---|
| 3 versus 4 digits | Fisher's $p = .004$ | Fisher's $p = .012$ |
| 4 versus 5 digits | $\chi^2 = 3.1$, $p = .04$ | $\chi^2 = 5.2$, $p = .01$ |
| 5 versus 6 digits | – | $\chi^2 = .3$, $p = .3$ |

[11] In the word length analysis, we did not include 3-letter words because they do not allow middle migration errors, which is our main interest. We also excluded the 7-letter words because there were only thirteen 7-letter target words, so a reliable comparison was not possible. In the number length analysis we included all the stimuli, including 3-digit numbers, because 3-digit numbers do allow for migration errors, as we will see later.

**Table 11 – The rate of adjacent and nonadjacent migration errors in word and number reading.**

| | | EY | YS |
|---|---|---|---|
| Words | Adjacent migrations | 21% | 12.5% |
| | Nonadjacent migrations | 9.5% | 4.6% |
| | Adjacent: nonadjacent ratio | 2.2:1 | 2.7:1 |
| Numbers | Adjacent migrations | 36.6% | 37.8% |
| | Nonadjacent migrations | 1.2% | 4.9% |
| | Adjacent: nonadjacent ratio | 30:1 | 7.7:1 |

on his reading of 619 words. Of these words, 580 had potential for a lexical migration in middle letters – adjacent (442 words) or nonadjacent (151 words).

The adjacency analysis (Table 11) showed more adjacent than nonadjacent migrations, $p \leq .01$, in both words and numbers, for both participants. However, this adjacency effect was much larger for numbers than for words: whereas in words nearly a third of the migrations were nonadjacent, in numbers there were almost no such migrations. The difference between words and numbers in adjacent to nonadjacent rates was significant (EY: $\chi^2 = 11$, $p = .004$; YS: $\chi^2 = 10$, $p = .007$).

2.2.6.3. The bathtub effect. One of the most robust characteristics of letter migrations in LPD, as described by Friedmann and Gvion (2001) and Friedmann and Rahamim (2007) is the *bathtub effect*: migrations in words occur mainly in middle letters, whereas first and final letters are resistant to migration. In reading words, each of the 11 participants with developmental LPD who participated in Part A had significantly more middle migrations than migrations involving an exterior letter (Friedmann and Rahamim, 2007), a difference that was significant also on the group level, with an average of 25.5% middle migrations and 4% exterior migrations. The superiority of the first and last letters over the middle letters was also found by Peressotti and Grainger (1995) and by Perea and Lupker (2003) for normal reading.

Does the bathtub effect exist for EY and YS, and, crucially, does it also extend to number reading? To assess these questions we analyzed the reading of the 326 words and 212 numbers they read in Experiment 3, comparing the rates of migrations that involved only middle letters, to migrations that involved also first or final letter. In words, we calculated the number of middle migrations out of the 280 words that had a lexical potential for such a migration, and the number of exterior migrations out of the 240 words with a potential for exterior migration, see example (3).

(3) Target word: ישרה (ISRH, yeshara, straight-fem)
Middle letter migration: ירשה (IRSH, yarsha, inherited-fem; or yarshe, will-permit-mas)
Exterior letter migration: שירה (SIRH, shira, poetry)

Fig. 2 compares middle migrations, exterior migrations involving the first letter or digit, and exterior migrations involving the last letter or digit. Both EY and YS made significantly more middle than exterior migrations in reading words (EY: $\chi^2 = 46.1$, $p < .001$; YS: $\chi^2 = 13.6$, $p < .001$), but significantly more exterior migrations in reading numbers (EY: $\chi^2 = 17$, two-tailed $p < .001$; YS: $\chi^2 = 14.5$, two-tailed $p < .001$). As can be seen in Fig. 2, the reason for the high rate of exterior migrations in number reading is that many of the migrations involve the last (rightmost) digit. Thus, whereas both participants showed the bathtub effect for word reading, it did not characterize their number reading.

2.2.6.4. Position of errors in number reading. Following the finding that migrations occur in different positions for words and numbers, we conducted a more detailed error-by-position analysis in numbers, hoping to learn about the way the visual analyzer processes numbers.

An issue that should be addressed when trying to define the position of errors in numbers is whether error positions in numbers of different lengths should be pooled together by aligning the numbers to the leftmost or to the rightmost digit. To check which of these is more appropriate, we analyzed the patterns of transposed digits in 4- and 5-digit numbers. In 4-digit numbers, almost all migrations were transpositions of the units digit and the tens digit (EY: 10 out of the 12 migrations; YS: 9/9). If numbers should be aligned to the leftmost digit, we should expect the migration error rate in 5-digit numbers to be high in the 3rd and 4th digits from the left, like in 4-digit numbers. If they should be aligned to the right, however, we expect migrations in 5-digit numbers to occur mostly in the two rightmost digits, and this is in fact what happened: the predominant pattern of migrations in 5-digit numbers was still units with tens (EY: 18/19; YS: 11/26. The second most frequent migration pattern of YS appeared only 5 times. Also, he made 9 migrations involving the rightmost digit, which involved the hundreds digits as well). Thus, migrations should be pooled together by aligning numbers to the rightmost digit.

In this analysis, we considered only cases in which the target digit was read correctly – in the correct or in an incorrect position. We excluded digits with identity errors (missing or substituted digits), because it is difficult to know in those cases whether this digit migrated. The calculated position was

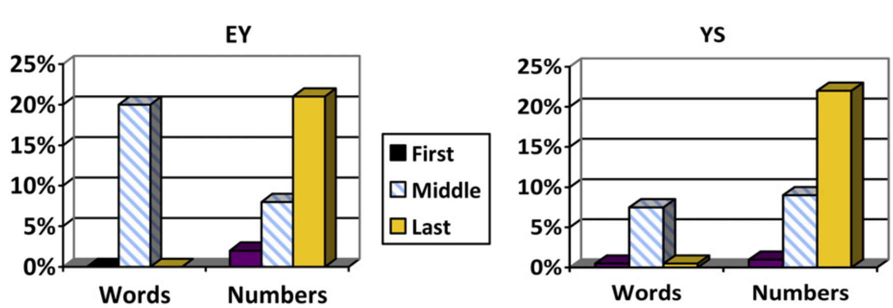


**Fig. 2 – The bathtub effect – middle versus exterior (first/last) migrations in number and word reading.**

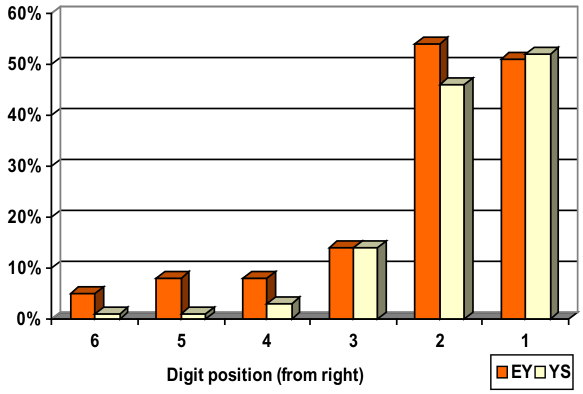


**Fig. 3 – The percentage of migration errors-by-position ("1" indicates the units position).**

that of the target digit. For example, if the number 123 was read as 134, we count the "3" as a migration in the units position, its position in the target number (rather than in tens position, its position in the response number).

Fig. 3 shows that the rate of migration errors increases as we get closer to the end of the number. This was an analysis of 3–6 digit numbers. The cleaner analysis of 4–5 digit numbers yielded a very similar distribution of errors-by-position. The position effect was significant: the rate of migrations in the hundreds digit was significantly lower than the migration rate in the tens digit – both in 4–5 digit numbers (EY: $\chi^2 = 42$, $p < .001$; YS: $\chi^2 = 8.4$, $p = .002$) and in 6-digit numbers (EY: $\chi^2 = 4.4$, $p = .02$; YS: $\chi^2 = 25$, $p < .001$). It was also significantly lower than the migration rate in the units digit (in 4–5 digit numbers, EY: $\chi^2 = 38$, $p < .001$; YS: $\chi^2 = 11.3$, $p < .001$; and in 6-digit numbers, EY: $\chi^2 = 4.9$, $p = .01$; YS: Fisher's $p < .001$). Also, the rate of migrations in the thousands digit was lower than in the hundreds digit in 4–5 digit numbers (for YS the difference was significant, Fisher's $p = .01$; for EY the difference was marginally significant, Fisher's $p = .06$).

The error-by-position analysis in Fig. 3 shows the position from which each digit migrated, but it doesn't show where it migrated to. In order to see this, we checked the exact pattern of migrations: we counted the number of times there was a migration between each two (or more) positions. This analysis is shown in Table 12, and includes only 4–5 digit numbers, which were the most reliable. The left column shows the positions of the transposed digits: for example, the first row in the table counts cases in which the two rightmost digits switched positions (e.g., 1234 → 1243), cases in which the units digits migrated to the tens position (e.g., "1234" → "124?"), and cases in which the tens digits migrated to the units position (e.g., "1234" → "12?3"). The fourth row counts migrations involving all the digits in the right triplet (e.g., 1234 → 1423).

The analysis shows that most of the migrations were transpositions of the units digits with the tens digit. For EY, this accounted for 90% of the migration errors. For YS, 57% of the migration errors were in the two rightmost digits, and 94% were in the rightmost triplet.

Table 11 included cases in which digits were transposed with digits that were omitted or substituted (shift and miss or shift and substitution). Excluding such identity errors would have made the pattern in Table 12 even more extreme: most of the identity errors are in the rightmost positions, and excluding them increases the rate of migrations in these positions. An even more conservative approach would be to completely exclude any number in which an identity error occurred, and analyze only clean transpositions. We performed this analysis, and the results were essentially the same as those shown in Table 12.

The findings regarding the position of migration errors can be interpreted in terms of attention: while reading words, attention is said to be first allocated to the first and the last letters, and only then to middle letters (Merikle and Coltheart, 1972; Bradshaw et al., 1977; Bradshaw and Mapp, 1982; Mason, 1982; Friedmann and Gvion, 2001), maybe because exterior letters are those that provide activation to a subset of candidate words when accessing the lexicon (Forster, 1976; Grainger and Segui, 1990). Attention to middle letters is assigned only later, and is allocated to all the middle letters together, therefore these letters are more prone to lose their relative positions. Applying the same logic to the findings about numbers, described in Fig. 3, leads to the conclusion that in number reading, unlike in word reading, attention is allocated sequentially, digit by digit, from left to right. The leftmost digits get attention first, and the attention binds them to their relative positions, so there are fewer position errors in them. The rightmost digits get the least and last attention, and are therefore subject to more migration errors. The length effect we found in number reading (see Fig. 1 above) becomes clearer if the allocation of attention is indeed sequential. Conversely, in word reading, where attention is allocated in parallel, no length effect was found. An interesting anecdote in this context is a remark made by EY while trying to explain why she made migration errors in the number reading task but not in the number repetition task: "I just don't have enough time to reach the last digits", she said. Her intuition becomes clear if indeed attention is allocated sequentially.

**Table 12 – Number of migration errors of each pattern in reading 4–5 digit numbers.**

| Migration position | EY | YS |
|---|---|---|
| □□□■■ | 28 | 20 |
| □□■□■ | 0 | 4 |
| □□■■□ | 1 | 5 |
| □□■■■ | 1 | 4 |
| Total right triplet | 30 | 33 |
| □■■□□ | 1 | 1 |
| □■□■■ | 0 | 1 |
| Total cross-triplet | 1 | 2 |
| Total | 31 | 35 |

The finding that most of the migrations are transpositions of the units and tens digits, as shown in Table 12 and in Fig. 3, may be explained in two ways. One explanation is that it may result from a combination of the tendencies to allocate attention sequentially left to right and to transpose adjacent digits: if attention is allocated to the digits in a sequential manner, the visual analyzer tends to transpose adjacent digits, and the last two digits get the least and latest attention, the result would be a large number of transpositions between the last two digits. Such a tendency to transpose adjacent digits is not surprising: we assume that like in word reading, allocating simultaneous attention to several symbols increases the probability of their being transposed. In sequential allocation of attention, no two digits get attention at the exactly same time window, but adjacent digits are the closest to this situation. Another possible explanation is that although attention is allocated to the digits sequentially, the last two digits are different and attention is allocated to them simultaneously. This explanation is more appealing in that it seems to fit better the overwhelming rate of migration errors in digits in these two positions compared with the other digits. A possible reason for allocating attention this way is syntactic: the transcoding of the last two digits into words is special for teen numbers. In English, as well as in Hebrew and many other languages, teen numbers are pronounced in reversed order – first the units digit and then the "teen" word, e.g., "14" is pronounced as "four; teen". In many languages, the two digits are pronounced as a single word. This irregularity may encourage simultaneous processing of the last two digits (see Cohen and Dehaene, 1991, regarding syntactic functions in the visual analysis of Arabic numbers).

An alternative pattern of attention allocation in number reading, according to which attention is allocated in parallel to groups of 3 digits at a time, is not supported by the facts: first, there were fewer errors in the hundreds digit than in the tens and units digits. Second, the 3-digit-grouping hypothesis predicts migration errors within triplets of numbers but not cross-triplet migrations, contrary to the findings: indeed, the number of migrations involving only the right triplet was high, but this is probably because there were more migrations at the end of the number. The comparison of cross-triplet migrations with migrations within the left triplet in 6-digit numbers, yielded no significant difference. For EY, 6 out of 33 migrations were cross-triplet and 7 involved the left triplet, $\chi^2 = .1$, $p = .76$; For YS the pattern was even reversed: there were 9 cross-triplet migrations but only 2 migrations which involved the left triplet.

Another alternative explanation to the error-by-position effect that can be ruled out was suggested by Hinrichs and Novick (1982, following Dale and Baddeley, 1966) in the context of free recall tasks. They suggested that magnitude estimation of the number being read served as an assisting factor, and helped in identifying the leftmost digits. This claim cannot account for the findings in digit migrations in reading, for two reasons: first, magnitude representation is thought to be an analog, inexact representation of the number, which can distinguish between numbers in ratio of no more than 7:8 (Van Oeffelen and Vos, 1982 found that magnitude perception has a Weber fraction of .163). We therefore cannot expect the magnitude perception to assist in identifying anything except the leftmost digit – it may tell us that 430 is different from 340, but not that 843 is different from 834. Hence, we should expect similar errors across all positions except the leftmost digit, but our findings were completely different: most migrations were in the two *rightmost* digits, and there were very few migrations in any of the other digits. Furthermore, if the pattern of errors across positions originated in magnitude perception, we would expect the comparison of numbers of different lengths to result in similar error distributions in different lengths when counting errors from *left*, but we found that the position should be counted from the *right*.

**Table 13 – The rate of errors in each position in the migration stimuli, in same–different decision (Experiment 7), and in sequence identification (Experiment 8).**

| | | Thousands–hundreds | Hundreds–tens | Tens–units |
|---|---|---|---|---|
| Same–different decision | EY | 30% | 33% | 78% |
| | YS | 10% | 13% | 26% |
| Sequence identification | EY | 13% | 5% | 60% |
| | YS | 7% | 10% | 15% |

Another explanation that should be discussed is that the error-by-position distribution was caused by the limited exposure in the reading tasks, and would not have existed in unlimited exposure. This claim is essentially identical with the sequential allocation of attention hypothesis, only put in other words: the participants "did not reach the end of the number" because the last digits were the last to get attention, and did not get it in time.

If the visual analyzer allocates attention to numbers in a serial manner, is this true only when reading aloud is required, or whenever written Arabic numerals are processed? If sequential allocation of attention is a general characteristic of Arabic number processing, we would expect to find it also in tasks that do not require Arabic-to-verbal transcoding. And, indeed, we do. Table 13 shows the error-by-position analysis on migration errors in the same–different decision and in sequence identification, two comprehension tasks which involve neither transcoding nor production of numbers. This analysis yielded a similar position effect in both these tasks: the rate of migration errors is higher in the rightmost digits than in the other locations, a difference that was significant, just like the pattern in reading aloud: pooling the two tasks together, EY: Fisher's $p < .001$; YS: $\chi^2 = 3.2$, $p = .04$.

Thus, a crucial difference between the processing of words and numbers is the allocation of attention: in words, attention is allocated first to the exterior letters and then to the middle letters, whereas in numbers attention is allocated to the digits serially, from left to right, possibly allocating attention to the two rightmost digits together.

#### 2.2.7. *Manipulating the visual analyzer*

2.2.7.1. Experiment 11: reading digital hours. Another task we used during this study was reading digital hours: EY and YS were presented with 28 4-digit numbers, each shown for 400 msec (i.e., under the same conditions as in the reading task in Experiment 3). They were instructed to read them as a time: for example, they were to read "1025" as "twenty-five past ten" (although the hour names in Hebrew are not irregular as in English, and the hour name is pronounced before the minutes, so 1025 is read as "ten twenty five"). The participants were also instructed to use the word "quarter" where appropriate rather than "fifteen", and "half" rather than "thirty", and to say times in each second half-hour related to the later rather than the earlier hour (i.e., they should read 1035 as "twenty-five to eleven" rather than "ten thirty five"). These instructions were aimed to encourage semantic processing of the number, so the participants would use the semantic route rather than the direct Arabic-to-verbal transcoding route. At the time this task was administered, we already had some evidence that the migration errors originate in the input modules, so we expected them to occur in this task too. But contrary to our expectations (and to the results of the other experiments in this study), the error rate of both participants in this task was very low, much lower than their error rate in reading 4-digit numbers in Experiment 3: EY had a single error (4%, *vs* 31% in 4-digit numbers in Experiment 3, Fisher's $p = .004$), and YS had three (11%, *vs* 36% in Experiment 3, Fisher's $p = .04$). Furthermore, none of these few errors was a migration error: they all seemed to be production-related. We set out to investigate this strange phenomenon.

2.2.7.2. Experiment 12: explicit allocation of attention. One explanation for the absence of migration errors in reading hours is that the difference resulted from the instructions to read the number as pairs rather than as a 4-digit number. To assess this possibility, we showed EY and YS a list of 82 4–5 digit numbers, and asked them to read them in a split manner: they were to read the 4-digit numbers as pairs ("3456" as "thirty four, fifty six"), and the 5-digit numbers as a pair and a triplet ("12345" as "twelve, three hundred and forty five"). The list of 82 numbers, which were part of the list the participants read in Experiment 3, included 42 4-digit numbers and 40 5-digit numbers. In this task too, both participants had significantly less migration errors when they read the numbers in a split manner than they had when reading the very same numbers in Experiment 3 (see Table 14).

Unlike in English, 4-digit numbers in Hebrew cannot be pronounced split into pairs. For example, the number 3456 cannot be read in Hebrew as "thirty-four hundred and fifty six", but only as "three thousand, four hundred and fifty six". Thus, the split and the whole-number pronunciations of 4-digit numbers in Hebrew are quite different. However, the split and the whole-number pronunciations of the 5-digit numbers in Hebrew (like in English), are almost identical: for example, "23456" should be read in this task as "twenty three, four hundred and fifty six", very similar to the way it was read in Experiment 3, which was "twenty three thousand, four hundred and fifty six". The difference is just a single word: "thousand". Interestingly, EY had almost no migration errors even when reading in a split manner even when considering only the 5-digit numbers, a significant difference from her reading results in Experiment 3 (Fisher's $p < .001$). YS had a non-significant decrease in the number of errors in 5-digit numbers compared with Experiment 3 (Fisher's $p = .18$).

**Table 14 – The rate of migration errors in standard reading (Experiment 3) versus reading the same numbers in a split manner (Experiment 12).**

| | | EY | YS |
|---|---|---|---|
| 4 digits | Standard reading | 28.6% | 21.4% |
| | Split reading | 2.4% | 10% |
| 5 digits | Standard reading | 47.5% | 45% |
| | Split reading | 2.4% | 33% |
| Sum | Standard reading | 38% | 34% |
| | Split reading | 2.4% | 21% |
| | Comparison | Fisher's $p < .001$ | $\chi^2 = 3.7$, $p = .03$ |

EY's pattern of results in this experiment was quite astonishing. She read the exact same numbers, which were presented in the exact same way, she said the exact same words (but one – "thousand"), and still her number of errors dropped from almost 50% to virtually no errors at all. In fact, we were so surprised by this finding that we made her read the 5-digit numbers in the regular fashion one more time, just to make sure that her dyslexia did not suddenly disappear. But it did not. In the standard reading, her migration error rate peaked again.

How did this happen? We assume that the instructions to read the numbers in a split manner made EY and YS allocate attention to the numbers in a different manner, and process each pair or triplet separately rather than the longer number as a whole. This is because the allocation of attention is guided by syntactic considerations, and the allocation of attention to a 5-digit number is different from the allocation of attention to 2 and 3 digit numbers. As a result, the migration error rate was reduced to their error rate in 2- or 3-digit numbers (which was close to zero). But why was EY unable to use the same attention-allocation strategy in 5-digit numbers, even after she knew that it gets her better results? We are quite sure that if EY *could* have used this strategy, she would: in many tasks we administered to her, she showed an impressive capability to identify strategies that assist her, and to use them. We therefore assume that there are certain processes in reading 5-digit numbers that prevented EY from using the splitting strategy. Syntactic analysis of the number may be such a process: when encountered with a 5-digit number, the visual analyzer may initiate a process of syntactic nature, that must analyze the whole number in order to create a syntactic frame for its production (McCloskey et al., 1986; McCloskey, 1992). Cohen and Dehaene (1991) suggested a process of a similar nature, that pre-scans the whole number for *syntactic markers* – 0's and 1's that modify the default mapping principles from digits to word names (e.g., the digit 1 in 813), and are therefore needed in order to create the number's exact *word frame*. Comparison of reading numbers with or without zero shows the effect of syntactic markers for EY as well – she had less errors when reading numbers with 0 (Dotan and Friedmann, in press). Interestingly, although syntactic markers had an effect on the migration error rate, visual markers such as a comma separator between the hundreds and the thousands digits did not seem to have an effect. EY's reading of 120 numbers, half of which were with comma separator, did not reveal any significant effect of the separator ($\chi^2 = .79$, $p = .38$).

These results are encouraging as they suggest that instructing individuals with digit-position deficits to read numbers in a split manner may serve as a work-around strategy and as a possible direction for therapy. These findings are in line with results regarding the treatment of LPD in words, and of attentional dyslexia, indicating that the presentation of words in a way that allows the separate allocation of attention to single letters of single words reduces the rate of migrations considerably (Rahamim & Friedmann, 2004; Shvimer et al., 2009).

## 3. Discussion

The comparison of number reading and word reading in LPD has implications for three related theoretical discussions: the first relates to whether the visual analysis stage in the reading process is domain-specific to orthographic-verbal material. Another concerns the characterization of the deficit in LPD and its source. A final issue relates to the characterization of the processes involved in reading numbers and words.

The main finding of this study is that words and numbers were processed differently by individuals with developmental LPD. Whereas all 12 participants showed a significant deficit in encoding the relative position of letters within words and made letter transposition errors in a quarter of the migratable words they read, 10 of them could read numbers normally. Their encoding of digit position within numbers was similar in all respects examined to that of the matched control participants: they did not make migration errors in reading numbers, and they were able to detect differences in digit order in a same–different decision task, which they were unable to do in words. Furthermore, the two individuals who did have a deficit in number reading, showed different patterns of errors in reading words and in reading numbers.

With respect to the question of the domain-specificity of the visual analyzer, these results provide a very clear answer. The letter position errors of the participants stemmed from a deficit at the visual analyzer, and specifically at the letter position encoding function of the visual analyzer. The fact that 10 of them did not show a position deficit in numbers indicates that the position encoding function of the visual analyzer is responsible for letters, but not for numbers: the visual analyzer is dedicated to the position analysis of orthographic material, whereas the early visual analysis of numbers is performed elsewhere. Thus, the visual analyzer is actually an orthographic visual analyzer.[12]

These findings also bear on the characterization of letter position dyslexia and its source. The dissociation between word and number reading refutes explanations of letter position dyslexia (and, consequently, explanations of developmental dyslexia in general) that ascribe it to a general perceptual deficit, such as a deficit in visual scanning (Ferretti et al., 2008): if a person has a perceptual deficit, it should affect both words and numbers. Our findings, however, were different: for 10 participants, only words were affected by the LPD, whereas number reading was spared. Thus, LPD does not originate in a general perceptual deficit. Furthermore, the dissociation rules out any explanation of letter position dyslexia as resulting from a global attentional deficit, such as a difficulty in parallel processing of symbols (Bosse et al., 2007; Lassus-Sangosse et al., 2008) or crowding (Spinelli et al., 2002). To explain the findings, any attentional deficit account should relate to an orthography-specific attentional deficit, which will allow for the observed distinction between words and numbers.

Let us be clear: we do not reject the claim that there are global deficits, cognitive or perceptual, that may interfere with reading processes in certain cases. In fact, we think it possible that some global deficit underlies the dyslexia of EY and YS. But global explanations lack the granularity level necessary to account for the findings in this study (and in other studies) with respect to the very clear dissociation between impaired word reading and intact number reading.

The second part of this study compared word and number processing by analyzing the reading of the two individuals who were impaired both in word and number reading, and provided further evidence for the difference between the processing of words and numbers. The patterns of migration errors in words and numbers were different: in word reading, migrations tend to occur mostly in middle letters, relatively sparing the exterior letters. In number reading, the rate of migration errors increases the closer the digit is to the right end of the number, and migrations between the tens and units digits are especially frequent. Interestingly, we found that the digit position should be analyzed according to its distance from the right end of the number rather than from its left end. The stimulus length affected migrations in numbers, but not in words. We also found that whereas migrations did occur in nonadjacent letters, albeit to a smaller extent than in adjacent letters, nonadjacent migrations almost never occurred in number reading. The different patterns of errors-by-position suggest that the allocation of attention to words and numbers is different: while reading words, attention is first allocated to the first and the last letter, and only then to middle letters. While reading numbers, attention is allocated to the digits sequentially, from left to right.

We also saw that in number reading, unlike word reading, there was a large number of miss and substitution errors, for which we used the term *identity errors*. We assumed that the miss and substitution errors reflect different strategies to cope with the situation of missing digit identity. We showed that the identity errors in number reading do not originate in the visual analysis system, so although they exist only in number reading and not in word reading, they cannot be taken as evidence for different processing of words and numbers. At most, if indeed these errors originate in the participants'

[12] An alternative explanation that was suggested to us is that it is the lexicon, rather than the visual analyzer, that is responsible for migration errors. However, three arguments prove that this is not the case. First, migration errors occur not only in words but also in non-migratable nonwords, namely, nonwords for which migration does not create any existing word. Friedmann and Rahamim (2007) reported that the participants in part A of this study made 12% migration errors in reading of non-migratable nonwords. Second, some children with surface dyslexia who have no access to the orthographic input lexicon also demonstrate LPD and migrations in middle letters (see for example Friedmann and Lukov, 2008). A third argument, detailed in footnote 5, is that not only migrations from infrequent to frequent migratable words occur, but also migrations in frequent words to their infrequent counterparts, a phenomenon which cannot be explained as induced by the lexicon.

reduced working memory, this may indicate that the number reading process relies more heavily on working memory than word reading; but this possibility was not thoroughly tested, as it was not the focus of this study.

Taken together, the findings regarding the dissociation between words and numbers, and the findings regarding the different patterns of attention allocation in word and number reading, suggest that visual analysis (or at least its position-encoding function) is performed by two separate modules: one module is restricted to words, and another module processes numbers. (The current study does not allow us to determine whether this second module processes only numbers or other types of stimuli as well.) These findings again indicate that the visual analyzer that is impaired in LPD (as well as in attentional dyslexia, and in some forms of neglect dyslexia and visual dyslexia) is domain-specific and acts only on letter input. A possible reason for having two separate visual analyzers is the different patterns of processing in words and numbers, such as the different pattern of attention allocation.

How does the reading system decide whether it should use the orthographic visual analyzer or a different one? Is this determined only by the type of symbols being read? Findings from neglect dyslexia (Friedmann and Nachman-Katz, 2004) suggest that it is not enough that the presented symbols are letters or digits, they also have to be interpreted as such: the left side of the same stimulus was neglected when it was interpreted as a word, and read correctly when interpreted as a number. In fact, the reading mechanisms may be more context-dependent than is usually acknowledged: the finding in the current study, that EY and YS could read numbers better in a split manner (in reading digital hours for example), is another effect of context on reading, and Cohen and Dehaene (1995) also described effects of context and task demands on the ability to read numbers.

The specificity of the visual analyzer to orthographic material is surprising when we think in evolution of the short time the human kind has been reading. What made the brain able to specialize in orthographic material? Further research and thought are required to solve this puzzle of, as Cohen et al. (2000; 305) put it, ''How the genetically determined organization of visual and verbal areas of the human brain interact with cultural factors to produce a well-defined cortical region responsive to words.''

A question that may be asked at this stage is why EY's and YS's letter position dyslexia extended to numbers, whereas the other participants' LPD was limited to word reading. A possible answer to this question is that the LPD of EY and YS originates in a global attentional or spatial deficit (encoding of letter or digit position is a procedure of a spatial nature), that affected their letter position as well as their digit-position encoding, whereas the LPD of the other participants was caused by a specific impairment in the orthographic visual analyzer. We did find some preliminary indications that EY had a broader spatial deficit – both in global tasks we administered her (such as 3D perception of perspective), and in reading tasks (she had some letter migrations between words). It would be interesting to assess, in further studies, whether general spatial and attentional abilities are correlated with migration errors in number reading, as well as word reading.

Although number and word processes are different, the source of migration errors in both is deficits in the input modules. LPD is said to originate in an impaired visual analyzer (Friedmann and Gvion, 2001; Friedmann and Rahamim, 2007), and this was the case for EY and YS as well. We showed that their digit migration errors in number reading also originated in an impairment in the input stages of the number reading and comprehension processes. As far as we know, only Noel and Seron (1993) reported a selective impairment in the input processes of Arabic number reading, which was in the syntactic part of the Arabic input module. The current study is the first to compare a deficit in the input modules in numbers and in words. The similarity that we found comes as no surprise: it was already suggested that number reading processes are similar in certain aspects to the word-reading processes (e.g., Cohen et al., 1994).

Finally, we saw that instructing the participants to read numbers in a split manner, as pairs and triplets, reduced the migration error rate. The improvement was dramatic for EY, and smaller, yet significant, for YS. We think that this method, or similar methods that manipulate the allocation of attention, should be further explored as a possible aid in their rehabilitation of position errors in number reading, and maybe of other dyslexias with an attentional nature.

## Acknowledgements

We are grateful to the participants, and especially to YS and EY, who sat through many tests and kept positive and interested, and to Ronit Szterman for her help in administering some of the tests in Part B. The research was supported by the Israel Science Foundation (grant no. 1296/06, Friedmann).

## Appendix A: Non-migration errors in number processing

In addition to their migration errors in number reading, EY and YS had several other types of errors in Experiment 3: they made *omission* errors, in which one or more target digits were missing in the number they said (e.g., reading 236 as 206 or 26). A slightly different type of errors were *miss* errors, in which they failed to name one digit or more, although they were aware that a digit was missing at specific positions (e.g., 74 → ''*Seventy something*''; or 156 → ''*One hundred and... I don't know, but it ends with a six*''). They also had *substitution* errors – producing a wrong digit name. The substitution errors were of three kinds: *Copy* errors, substitutions with a digit that exists in the target number in a different position (e.g., 12395 → 12393); *buffer migrations*, in which the response digit appeared in the same position in the previous number (because the numbers were presented one at a time on the computer monitor, this cannot be attributed to migration from a neighboring number, but rather to lack of clearing of some buffer. See Friedmann et al., in press for the presentation of buffer migration errors in attentional dyslexia); and *intrusions*, other substitutions that cannot be accounted for by the existence of the response digit within the number or in a previous number.

Copy errors can be interpreted either as substitutions or as migrations in which a digit migrates to a new location in the number *and* remains in its original position (for a related discussion of copy errors in words see Friedmann and Rahamim, 2007). To check which alternative is more likely, we compared the rate of copy errors with the probability that a random substituted digit will exist somewhere else in the number: for example, in 5-digit number with 5 different digits, the erroneous digit has a probability of 4/7 to be identical by chance with one of the other digits in the number (as only the digits 2–9 were used, there are 7 possible substitution errors for each digit). This analysis was carried out only for YS (because EY did not have enough substitution errors), and showed that the number of copy errors did not differ from the number of copy errors expected as a result of random substitutions. In fact, contrary to the hypothesis that copy errors are migrations, their rate was even *lower* than expected by chance. Thus, copy errors were counted as regular substitutions and not as migrations. Note that copy errors were counted separately from migrations in the word-reading task too (as discussed in Experiment 3).

Buffer migrations, on the other hand, proved to be more frequent than expected by chance, and were therefore counted separately from other substitutions. In the number reading task (Experiment 3), YS substituted 39 digits, 16 of which appeared in the same position in the previous number. This number was compared with the expected rate of buffer migrations (1/7), and the difference was significant ($\chi^2 = 6.8$, $p = .005$). The number of substitutions EY made was too small to make a similar analysis. Table 15 analyzes the various types of errors EY and YS had in the number reading and number repetition tasks.

### A.1. *Identity errors: do they originate in an input module deficit?*

Having seen the high rate of identity errors (misses and substitutions) in the number reading task, we wanted to find out whether these errors are related with the migration errors, or whether they are caused by different reasons, and should be analyzed independently of the migrations. Identifying the locus of impairment that caused these errors should help answering this question. If they are caused by an input module deficit, like the migrations, we should explore the relation between them. If, however, they are caused by a completely different deficit, then each type of error can be analyzed and discussed independently.

The analysis of error types revealed different patterns for migration errors versus identity errors: in the number reading task, the participants had migrations as well as identity errors (with EY making more miss errors, and YS more substitutions). In the number repetition task, there were virtually no migration errors, but there was a significant rate of identity errors (substitution errors, compared with zero, EY: Fisher's $p = .01$; YS: $p < .001$; miss errors, EY: Fisher's $p = .03$; YS: $p = .06$). This pattern was the first finding that led us to conclude that the origin of the identity errors is different from that of the migration errors: whereas migration errors originate in the input reading modules, as we already saw, identity errors seem to originate in post-input processes. Another evidence that locates the identity errors in a post-input stage is the analysis of mixed shift-and-miss or shift-and-substitution errors, which we described earlier (in Section 2.2.5). This analysis showed that the identity errors occur at a later point in time than the migrations. Regarding the number repetition task, in which auditory input was required, we

**Table 15 – Percentage of errors of various types in number reading and repetition.**

| | | No. of digits | No. of items | All errors | Migration | Substitution | Miss | Miss and substitution | Omission |
|---|---|---|---|---|---|---|---|---|---|
| EY | Reading | 3 | 50 | 6 | 6 | 0 | 0 | 0 | 0 |
| | | 4 | 42 | 31 | 29 | 2.4 | 2.4 | 2.4 | 0 |
| | | 5 | 40 | 75 | 48 | 2.5 | 38 | 40 | 0 |
| | | 6 | 80 | 96 | 41 | 10 | 95 | 96 | 0 |
| | | Total | 212 | 58 | 32 | 5 | 43 | 44 | 0 |
| | Repetition | 4 | 42 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 5 | 40 | 25 | 2.5 | 15 | 13 | 25 | 0 |
| | | Total | 82 | 12 | 1 | 7 | 6 | 12 | 0 |
| YS | Reading | 3 | 50 | 4 | 4 | 0 | 0 | 0 | 0 |
| | | 4 | 42 | 36 | 21 | 19 | 0 | 19 | 0 |
| | | 5 | 40 | 75 | 45 | 48 | 10 | 55 | 5 |
| | | 6 | 80 | 100 | 50 | 11 | 99 | 99 | 0 |
| | | Total | 212 | 60 | 33 | 17 | 39 | 51 | .9 |
| | Repetition | 4 | 42 | 2.5 | 0 | 2.5 | 0 | 0 | 0 |
| | | 5 | 40 | 40 | 10 | 33 | 10 | 35 | 0 |
| | | Total | 82 | 21 | 5 | 17 | 5 | 18 | 0 |

Note. The type-specific errors do not sum to the total number of errors because the participants occasionally made more than one error per number.

could see that the participants' auditory input and auditory discrimination were unimpaired, as indicated by their flawless repetition of migratable words, non-migratable words, and nonwords (Experiment 6), and by their flawless performance on the auditory discrimination test Hebrew SPAC (Rich et al., 2008). These tasks showed also that their phonological output was unimpaired, as did the fact that they did not have problems in spontaneous speech.

Taken together, these findings suggest that identity errors do not originate in the input modules but in a production-related deficit, and it therefore seemed reasonable to analyze them separately from the migration errors.

### A.2. *Working memory as the origin of identity errors in number production*

The number production tasks involve working memory and verbal production. Thus, the impairment that caused the high rate of identity errors should stem from a deficit in one of these modules. Their phonological output, as already noted above, seemed intact, but their digit spans were limited: we assessed digit spans using the FriGvi test battery for working memory (Friedmann and Gvion, 2002; see Friedmann and Gvion, 2007 and Gvion and Friedmann, 2008 for a description of this battery). EY's digit span was 5, and YS's was 5.5, spans that are lower than the average digit span of 81 Hebrew-speaking individuals aged 20–40, which is 7.15 (SD = 1.11). The difference was significant for EY, Crawford's $t(80) = 1.93$, one-tailed $p = .03$, and marginally significant for YS, $t(80) = 1.48$, $p = .07$. Given this working memory limitation, it seems reasonable their high rate of identity errors resulted from their limited working memory.

If working memory was indeed the source of the identity errors in the number repetition task, miss and substitution errors may reflect different strategies to cope with the low memory span: both participants did not remember some of the digits in many cases; but while YS took a guess, EY preferred a more conservative strategy and said she did not know what the target digit was. A suggestion along the same lines was made by Butterworth (1979), who analyzed neologisms produced by the aphasic patient KC. Butterworth suggested that producing a neologism is a strategy for coping with a complete or partial failure to retrieve a word. Butterworth found that some of the neologisms were phonologically similar to the target word or to prior or following words, and suggested that this phenomenon reflects cases where KC could retrieve only partial phonological information for the target word. In this respect, YS's large number of perseverations (30% of his substitution errors) can be interpreted as a parallel to those cases in which KC produced a neologism bearing phonological similarity with prior words: in both cases, the perseveration may fill in for missing information.

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