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The developmental trend of transposed letters effects in masked priming.

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One of the most intriguing ways to investigate early orthographic processing during reading is to examine the effect of letter transposition. This consists in transposing two letters of an existent word so that a nonword is formed containing the same letters as the original word, but in different positions (e.g TALBE from TABLE). The performance with nonwords with transposed letters (TL) is compared to a control condition in which the two transposed letters are replaced with two letters (RL) not contained in the words (e.g. TASDE). This effect has been used to separate the influence of letter position in contrast to that of letter identity in word recognition. Apparently, letter transposition effects are very easily undetected even by expert readers, with more lexical decision errors on TL stimuli (jugde) than on RL stimuli (jurpe); also TL nonwords are more slowly rejected as nonwords than RL nonwords (Colombo, Sulpizio & Peressotti, 2017; Grainger, Lété, Bertand, Dufau, & Ziegler, 2012; O'Connor & Forster, 1981; Perea & Fraga, 2006). In masked priming, TL nonwords prime the base word from which they are derived (jugde-judge), producing more facilitation compared to a RL nonword prime (Forster, Davis, Schoknecht & Carter, 2007; Lupker, Perea & Davis, 2008; Perea & Lupker, 2003a; 2003b; 2004; Schoonbaert & Grainger, 2004). Despite the wide literature on this phenomenon, several aspects related to the nature of TL effects and the way in which they occur are still unclear.

A critical open issue is the extent to which TL effects appear during reading development and how they can be accounted for by developmental models of reading. Two main paradigms, masked priming and lexical decision on nonwords derived by transposing or substituting letters of real words, have been used to investigate how TL effects are modulated during learning to read. Considering the developmental trend of masked priming effects, the results of several studies are divergent. In a longitudinal study, Castle, Davis, Cavalot and Forster (2007) tested children in third- and in fifth-grade with TL stimuli like lpay-PLAY and one-letter different stimuli (rlay-PLAY). The task was masked primed lexical decision. They found facilitatory priming for TL stimuli in third-grade children, but not in fifth grade-children, nor in adults. The authors suggested that lexical recognition is at the beginning “broadly tuned”, that is, operated by a not very precise mechanism, which explains why letter position is more easily neglected. With the increase in reading ability, lexical tuning mechanisms become more refined and a decrease in TL effects is thus expected. However, in the study, stimuli contained external TLs (beginning and end of stimuli), which have been shown to produce smaller priming effects than internal transpositions. Thus, their result might be a consequence of the type of manipulation used, and therefore cannot be counted as evidence for a developmental decrease in TL effects.

Acha and Perea (2008) tested third-grade and sixth-grade children and adults with masked priming. In the analysis of the raw data they found decreasing TL priming effects, with an average of 53 ms for beginning readers and around 11 ms for intermediate readers and adults. Acha and Perea also analyzed standardized data, because, as many authors now acknowledge, when there are strong differences in the global speed of different groups, in order to measure differences in the size of the effects of an interaction involving groups it is more appropriate to standardize the data (Faust, Balota, Spieler, & Ferraro, 1999). Acha and Perea found a significant interaction between TL priming and age with standardized data, thus concluding that in their study TL priming effects tended to decrease. However, sometimes the direction of the differences in the interactions may change when considering raw data and/or z-score-transformed data. For example, Ziegler, Bertrand, Lètè and Grainger (2014) tested children from the first to the fifth grade with a masked priming lexical decision paradigm, contrasting on one hand the TL with the RL conditions and on the other hand pseudohomophones with non-homophone control nonwords. With standardized data, they found that the size of the facilitation effect for the TL condition increased with age. However, considering the pseudohomophone effect, it remained constant in the standardized data, while the raw data showed an increasing trend, which suggests that looking at trends in raw data alone can be misleading.

In a more recent study, Kezilas, McKague, Kohnen, Badcock, and Castles (2016) argued that the most sensitive measure to understand the way letter position is processed is not the facilitation of TL primes (jugde) compared to RL primes (juple), but their cost compared to identity primes, because in RL primes not only letter position but also letter identity is changed, whereas in the comparison of TL and identity primes the only change is in letter position. Indeed, they measured TL costs as the difference between the TL condition (litsen-listen) and the identity condition (listen-listen) and TL priming effects in the usual way. They found that the size of the TL cost increased with age, mainly due to a steady decrease in latencies in the Identity condition, while TL facilitatory effect (RL-TL) remained constant. The developmental pattern obtained by Kezilas et al.,'s (2016) is not clearly interpretable. The TL cost increasing with age suggests that letter position is coded very early, and therefore that children might be using phonological processes, for which both letter identity and position are required. It also suggests that these processes are used more and more as children become expert readers. In contrast, the TL facilitation is constant, indicating that even young children might be using very flexible orthographic mechanisms, and not a phonological recoding procedure, requiring precise coding of letter identity and position.

In contrast to this pattern there are data from parafoveal preview effects in sentence reading. Tiffin-Richards and Schroeder (2015) compared TL, identity and RL conditions with the boundary paradigm (Rayner, 1975) in German adults and children. They found TL costs (TL-identity) for children of all ages, but not for adults, while TL facilitation (TL-RL) was evident in adults but not in children. The crucial difference, with respect to the developmental trend of the effects, is that Kezilas et al., (2016) found clear TL facilitatory effects since the early stages of reading acquisition whereas Tiffin-Richards & Schoreder, (2015, see also Leté & Fayol, 2013; Ziegler et al, 2014) did not report those effects in the early stages.

Grainger and colleagues (2012), using lexical decision on nonwords created by transpositions/replacement from real words, reported an increase in TL effects with age.

Specifically, the authors reported a parabolic trend, with the difference in latencies between TL and RL first increasing and then decreasing along the continuum of the first-to-fifth elementary grades. On the basis of these and Ziegler et al.'s (2014) data, it has been proposed that orthographic processing is carried out by two mechanisms. The first mechanism, called "coarse grained", is the result of the learning of connections between parallel orthographic letter coding and semantics; the second, more refined, mechanism is less tolerant to changes in position and identity of letters. When children start reading they use the phonological recoding mechanism, but with greater exposure to words, an increasing number of connections between patterns of letters and meanings are formed, leading to the build up of the so called orthographic lexicon. The coarse mechanism is exploited by expert readers, as suggested by reliable TL effects in adults, indicating that access to semantics can be reached without a precise coding of letter positions. Thus, according to this view, and in contrast with Castle et al.'s (2007) and Kezilas et al.'s (2016) study, children in the early stages of reading development should show little or no TL priming effects, because (a) they predominantly use the phonological recoding procedure, by which both letter identity and position are coded precisely, and (b) connections between grapheme clusters and semantics are not yet formed. TL effects however should increase in size with reading ability. Consistent with this hypothesis, Eddy, Grainger, Holcomb and Gabrieli (2016) measured EEGs in children aged between 8 and 10 years comparing TL and pseudohomophone priming effects. Both TL and pseudohomophone priming effects were evident in the N250 and N400 components, however only TL priming effects correlated with reading ability, signaling that the more skilled readers were increasingly using flexible orthographic mechanisms. This results is consistent with the hypothesis of multiple mechanisms for orthographic coding (Grainger et al., 2012; Ziegler et al., 2014) which assumes that becoming expert readers implies moving progressively from a slow and effortful decoding procedure to an automatic orthographic process, able to recognize orthographic units of gradually increasing size (Share, 1995; Ziegler & Goswami, 2005). It is especially interesting to investigate this transition using a language with transparent grapheme-to-phoneme mapping, in which the phonological procedure, though being effortful at the very beginning, rapidly becomes fast and automatic. Thus, children might simply automatize the phonological procedure based on an extremely fast process of coding and assembling single letters (fine grained mechanism). In such a case, is the development of a coarse-grained orthographic mechanism delayed or not implemented at all?

A first answer to these questions comes from a recent study. Colombo et al. (2017) tested second, third and fifth grade children and a group of adults with a lexical decision task on TL/RL nonwords derived from Italian words. As noted, Italian is a language with a high degree of transparency between orthography and phonology. Colombo et al. found that TL nonwords were slower than RL nonwords and this difference (measured on standardized data) increased with age, being already visible in third graders. This result suggests that the coarse-grained orthographic procedure develops early during reading acquisition even in languages with transparent orthographies. In the present study we aimed at replicating this effect with masked priming, where the prime is not visible and processing of the prime is completely automatic.

In their study, Colombo et al. also investigated the effect of position of TL/RL within each word. There were two conditions, initial and final transpositions (respectively, ABLERGO-ACMERGO from ALBERGO, *hotel*; LEOPADRO- LEOPATSO from LEOPARDO, *leopard*), never involving initial or final letters. The results showed a position effect, such as the increase with age in the TL effect was more marked in final than initial transpositions/replacements. This serial position effect suggested the involvement of a sequential mechanism. Thus, the second aim of the present study was to further investigate this serial effect with a different paradigm. The serial effect in lexical decision to a nonword might be due to the involvement of a phonological mechanism. Indeed, the phonological procedure is typically assumed to be working serially from left to right, therefore a letter transposition or replacement in the initial part of the prime would change the nature of the prime, and the target word might not be activated or its neighbors might inhibit it before it has a chance to compete. When the transposition is towards the end of the string, the first part of the nonword might provide stronger evidence for a "word" response, compared to when the transposition involves the initial part of the word. In Italian the root is at the beginning, and provides the most important information for the recognition of a word (e.g., Marelli, Amenta, Morone, & Crepaldi, 2013; Marelli & Baroni, 2015), while the final part is generally composed of morphological suffixes providing number and gender information. Thus, disrupting the final part should not hinder access to the lexicon. Another explanation of the position effect, within the general idea of serial processing, could be in terms of sequential processing within the coarse – grained orthographic procedure, as proposed by some models of letter position coding (Davis, 2010; Whitney, 2001). According to the SERIOL model, for example, orthographic coding requires labelling the position of each letter in the sequence and this process occurs serially, with activation of each letter rising and falling before the next one is activated. Thus, a serial position effect might also be interpretable within this model.

In the present study we investigated the serial position effect with masked priming lexical decision, in order to see whether it replicated with a different paradigm. As Ktori, Kingma, Hannagan, Holcomb and Grainger (2014) noted, "TL priming is believed to arise mainly from an orthographic level of processing driven by a mechanism that maps position-coded letter identities onto whole-word orthographic representations (Grainger, 2008)". Thus, if the serial position effect is driven by activation in the coarse-orthographic procedure, it is expected to be apparent also in a priming paradigm in which the prime is masked and the target is a word. In contrast, the absence of such an effect with this paradigm would speak in favor of a phonological origin of the position effect, that is, of a phonological effect induced by the nature of the experimental targets: TL/RL nonwords. That is, nonwords are more likely to be scanned serially, and to give rise to sequential effects.

We conducted a masked prime lexical decision experiment with children and adults in order to investigate the developmental trend of the priming effect, manipulating the position of the transposition in the prime. The same base word was used to derive two TL nonword primes, one with the transposition in the initial and one with the transposition in the final part of the string (ABLERGO and ALBEGRO from ALBERGO). The priming effect obtained in these conditions was compared to the priming effect obtained in the RL control conditions, where the two transposed letters were replaced by two letters non included in the base word (ACMERGO, ALBEMCO). If position effects are absent in this condition, we might conclude that the sequential effect found in Colombo et al. (2017) was due to the influence of a sublexical phonological mechanism in the lexical decision processes. In contrast, if the position effect survives even with a masked priming paradigm, this would be clear evidence in favor of serial processing even for the computation of a coarse orthographic code.

Materials and Methods

Participants.

One-hundred and three elementary students – 43 second graders, 22 third graders, and 38 fifth graders – were initially involved in the study. In order to take part to the study, parents and school director gave informed consent. All the students had typical development (as stated by teachers); they performed a partial version of the standardized test of word reading (Sartori, Job & Tressoldi, 1995) and the experiment. From the initial sample, 9 second graders, 3 third graders, and 6 fifth graders were excluded either because their native language was not Italian or because their standardized reading score was below 2 SD from the expected level. The final sample was composed of: 33 second graders (17 males; mean age = 7.21 years, SD = 0.40), 19 third graders (11 females, mean age = 8 years, SD = 0.45), and 32 fifth graders (16 females, mean age = 10.25 years, SD = 0.50). Children were tested during the first months of the academic year in a quiet room in their school. A group of 20 adult Italian native speakers (14 females; mean age = 24.8 years, SD = 3.21) was also collected; they were students of the University of Padua. All participants had normal or corrected-to-normal vision.

Materials and Design.

One-hundred words were selected as targets (mean letter length: 7.46, SD: 0.59; adult frequency (from CoLFIS, Bertinetto et al. 2005): mean: 121.16, SD: 148.14; child frequency (from Marconi, Ott, Pesenti, Ratti, & Tavella, 1994): mean: 78.01, SD: 202.67). For each target (e.g., *verdura*, vegetable), four types of prime were created (see Appendix): 1) transposed-letter (TL) prime with initial transposition (e.g., *vredura*); 2) RL prime with initial substitution (e.g., *vusdura*); 3) TL prime with final transposition (e.g., *verdrua*); 4) RL prime with final substitution (e.g., *verdoca*). TL primes were created by switching the position of two internal letters of the target, whereas RL primes were created by replacing the two transposed letters with two different ones; transposition and replacement never involved the first or the last letter. The four sets of primes were matched on the main psycholinguistic variables (see Table 1; all ps >.05); moreover, across the sets, transpositions and replacements involved either consonant clusters (CC), or consonant and vowel (CV-VC) adjacent letters, in the same proportion. The list of word primes is shown in the Appendix, where transposed and replaced 1 and 2 refer to the position of the TL/RLs.

One hundred pronounceable nonword fillers were created by replacing one or two letters from existing words of comparable length as the target words. Two types of primes were derived from each nonword, one in which two letters were replaced and one in which two letters were transposed; first and last letters were never changed. The nonword stimuli were included for the accomplishment of the lexical decision task and were not considered in the analyses.

Four different experimental lists were created so that each participant saw all the targets, but only paired with one prime – i.e., initial TL, final TL, initial RL, final RL –. Across participants each target was paired with all its four primes. In each list, the four types of primes were equally represented (25 stimuli each for a total of 100 experimental stimuli, see Appendix). Each list also contained 100 nonword fillers.

-insert Table 1 about here-

Procedure.

Participants were tested individually in a quiet room. They were instructed to decide whether each stimulus was a real word or not. In performing the task, participants were instructed to be as quick and accurate as possible. Stimuli were presented on a laptop computer screen, and the experiment was run using E- Prime software (Psychology Software Tools, Pittsburgh, PA, USA).

To amplify the priming effects, the sandwich priming procedure was implemented (Lupker & Davis, 2009). Each trial started with a fixation point (*) that lasted 1000 ms, and was followed by the target word/nonword in lowercase characters for 27 ms, in the same location as the fixation. The target was followed at the same location by a prime in lowercase characters for 70 ms. Finally, the target was again presented but in capital letters, and remained on the screen until the participant responded, or for a maximum of 5 seconds. Participants responded by pressing either the “m” or the “z” keys of the keyboard. They were instructed to decide as quickly and accurately as possible if the letter string they saw on the screen was a real word or an unfamiliar word. Participants were randomly assigned to one of four experimental lists so that there was an equal number of participants in each. The experiment was preceded by a practice session of 24 trials.

Results

One second grader was excluded from the analyses because of the very low accuracy (3 standard deviations below the second graders’ accuracy mean). Both reaction times (RTs) and accuracy were analyzed by means of a type of prime (TL or RL) position of the letter change (initial or final) and group (second graders, third graders, fifth graders, or adults) as a between-participants factor. In the by-items analysis, all factors were within items. Means are reported in Table 2.

– Insert Table 2 about here –

Accuracy.

Overall, accuracy was rather high. The ANOVA on percentage of accuracy showed main effects of group (F1 (3, 100) = 6.36, p <.001, η^2 = .08; F2 (3, 297) = 10.33, p <.001, η^2 = .02) and type of prime (F1 (1, 100) = 14.12, p <.001, η^2 = .02; F2 (1, 99) = 14.97, p <.001, η^2 = .009). Moreover, a significant two-way interaction between group and type of prime emerged (F1 (3, 100) = 6.51, p <.001, η^2 = .03; F2 (3, 297) = 7.17, p <.001, η^2 = .01). No other effect was significant. Multiple comparisons (Bonferroni corrected) indicated that type of prime was significant in adults only (p <.001, all other ps >.9).

Latencies.

Only responses to correct words were analyzed. RTs shorter than 300 ms or longer than 5000 ms were discarded (1.68% of the data points). RTs that were 3 standard deviations beyond the mean of children participants and 2.5 standard deviations beyond the mean of adult participants were also excluded as outliers (0.5% and 2.2% of all data points, respectively). We followed the same approach used on previous research on the developmental trend of TL effects (Lété & Fayol, 2013; Ziegler et al., 2014): First, we performed the ANOVA on inverse-transformed RTs (-1000/RT), which reduced the skewness of the distribution; then, if a two-way interaction with group emerged, we investigated it by transforming raw RTs of all four groups (second, third and fifth grades, and adults) into z-scores; this allowed us to control for general processing speed and verify the size of the effects avoiding over-additivity effects (Faust, et al., 1999) while investigating whether the size of the effects varied with age/reading ability. *Z*-score transformations relate to participants ‘ variability, thus only by-participant analyses are reported.

The ANOVA on inverse-transformed RTs showed main effects of group (F1 (3, 100) = 234.5, p <.001, η^2 = .86; F2 (3, 294) = 9757, p <.001, η^2 = .93;) and type of prime (F1 (1, 100) =

147.61, $p <.001$, $\eta^2 = .003$; F2 (1, 98) = 140.3, $p <.001$, $\eta^2 = .004$); the group by type of prime interaction was also significant (F1 (3, 100) = 50.65, $p <.001$, $\eta^2 = .003$; F2 (3, 294) = 35.62, $p<.001$, $\eta^2 = .004$). Neither the effect of position nor any interaction with position were significant. Multiple comparisons (Bonferroni corrected) showed that the effect of type of prime was significant in fifth graders (t (63) = 6.39, p <.001) and adults (t (39) = 12.57, p <.001), but not in second and third graders (both ps >.1). To obtain reliable estimates of the interaction we used z-transformed RTs. The group x type of prime interaction was significant, (F1 (3, 100) = 30.03, p <.001; F2 (3, 294) = 43.68, p <.001). Analyses performed on the different groups showed the same pattern found using non-standardized RTs: The effect of type of prime was significant in both fifth graders (t (63) = 6.57, p <.001) and adults (t (39) = 12.47, p <.001), but not in second and third graders (both ps >.9).

Insert Figure 1 about here

In order to verify if the priming effect tends to increase or remains stable with the increase in age, we investigated the linear and quadratic trend. The difference between the mean z-transformed reaction times in the TL and the RL conditions for each participant (priming effect) was calculated, combining initial and final positions, as there was no effect of the variable position of transposition. The independent variable was given by the mean-centered levels of the group variable. Two regression analyses were run on the z-transformed priming effect, one to investigate the linear trend, and one to investigate the quadratic trend. In the latter analysis the levels of the independent variable were the squared values of the mean-centered group variable. The first regression showed a significant linear trend ($R^2 = .44$; F(1,102)= 82.55, p = .000, see Figure 1). The inclusion in the model of the quadratic variable produced a 2.6% increase in the variance accounted for, which was also significant ($R^2 = .46$; F(1,101) = 5.06, p = .027).

We also calculated the correlations of the priming effect with the scores obtained by the reading lists, limited to children, as the test was not assigned to adults: there was a significant correlation between the priming effect and both the error scores ($r = -.36$, $p < .001$) and the reaction times of the lexical decision list ($r = -.27$, $p < .01$) with larger priming in participants who were faster and made fewer errors.

Insert Figure 2 about here

General Discussion

In the present study we investigated the effect of TL primes with children and adults in a masked lexical decision paradigm. In both latencies and accuracy, we found a priming effect that increased with age. The regression analysis on the z-transformed RTs showed both a linear and a quadratic trend of the priming effect, with its size increasing linearly, but less in second- and third-graders. We also investigated the effect of the position of the transposition, but this variable did not modulate the size of the priming effect.

Formerly (Colombo et al., 2017), using TL nonwords in a lexical decision task we found that the TL effect depended on the position of the transposition, with final transpositions (ALBEGRO, from *albergo*, hotel) showing larger effects than initial transpositions (ABLERGO from albergo). In Colombo et al.'s (2017) study, serial processing due to phonological involvement may have been boosted by the paradigm adopted in the study, in which nonwords were presented in lexical decision: in reading nonwords a sublexical mechanism is more likely to be involved. By shifting to masked priming we have made serial processing less influential also because priming was measured on target words, and not on a transposed nonword. Moreover, masked priming with very short SOAs is more likely to tap early orthographic levels of processing.

An alternative explanation we had proposed for the serial position difference in the priming effect was in terms of an orthographic mechanism specifying the position of each letter sequentially, as in the SERIOL model. However, as this mechanism would serve the specification of letter position for word recognition, it was proposed as a general mechanism that should work to a certain extent independently of the paradigm, and whose effect should be apparent also with masked priming. The lack of a position effect in priming suggests instead that the prime's letters were processed in parallel (e.g., Grainger, Dufau, & Ziegler, 2016). As we found no effect of position, we can therefore conclude that the sequential effect in the former study was encouraged by the paradigm used. Thus, an important point to make presently is that the processes involved in the transposition effect must be interpreted within a model of the task.

As noted in the introduction, the literature on the developmental trend of TL masked priming effects shows little agreement among the different studies, and two contrasting hypotheses have been proposed. According to the first, the lexical tuning hypothesis (Castle et al., 2007; Kezilas et al., 2016), during the early stages of reading development children mostly rely on a mapping from orthography to learned lexical representations, and adopt a lenient criterion with regard to the position of letters, while considering more precisely letters identity. With the increase in experience, reading processes become more precise and accurate. Thus, this hypothesis would predict larger TL effects in young readers, while, as reading experience increases, TL effects should decrease.

Differently, the second hypothesis, advanced in the framework of the multiple-route model (Grainger et al., 2012; Ziegler et al., 2014) makes the opposite prediction: TL priming effects should be weak (or absent) at the beginning of reading development, since beginning readers use mostly a phonological recoding procedure, which is very precise in the encoding of both letters identity and position. When orthographic processing starts to develop, the mapping from the input to the lexical representation may proceed in parallel, exploiting a coarse orthographic representation, which neglects precise letter position. Indeed, this neglect, together with the occurrence of TL effects in adult participants, is a well ascertained fact. This suggests that, for skilled readers, in order for reading to proceed quickly, it is preferable to use a parallel-but-less precise procedure, than a slower-but-more accurate procedure. Following this reasoning, TL effects are expected in more skilled readers, independently of whether masked priming or lexical decision to nonwords are used; empirical findings have supported this prediction, and TL effects have been repeatedly reported with adult readers (e.g., Colombo et al., 2017; Grainger et al., 2012; Perea & Lupker, 2003 a, b).

Granted the robustness of the TL effect in expert readers, the developmental trajectory of such an effect remains to be understood; that is, it is unclear whether TL effects are more apparent in beginning readers and then decrease, as predicted by the lexical tuning hypothesis (Castle et al., 2007), or whether they are small, or absent, in the very early period of learning to read and then increase *tout-court* – as predicted by the multiple-route hypothesis (Grainger et al. 2012; Ziegler et al., 2014). The present results are not consistent with the lexical tuning hypothesis, as we have found that TL priming effects were present in adults and fifth graders, but absent in younger children. Moreover, the regression analysis showed that priming effects increased with age, a pattern that is more compatible with predictions of the multiple-route hypothesis. In fact, the same trend was also reported in our previous study with the nonword lexical decision paradigm (Colombo et al., 2017), in which TL effects were found to increase with reading experience. Figure 1 shows that z-scores transformed latencies tend to increase with age/reading experience for the RLs condition, while they decrease in the TLs condition. This pattern might be interpreted as an effect of a more accurate check carried out on RLs when competition among the target word’s neighborhood does not allow an immediate decision because of the substituted letters. In contrast, more experienced readers tend to increasingly use a coarse orthographic procedure when all letters of the target word are present, although in a different position.

Insert Figure 2 about here

However, a different pattern was reported by Kezilas et al. (2016), who found that the difference between TL and RL conditions remained constant with the increase in reading experience. Thus, although they found a priming effect similarly to the present study, the size of their effect did not increase with participants' reading experience. We underline that even if we consider only the fifth-graders and adults the linear trend is significant ($R^2 = .36$; $F(1,50) = 28.26$, $p = .00$). Thus the size of TL priming keeps increasing with age. However, Kezilas et al., (2016) also included a different manipulation, considering the cost of transposing letters, compared to the identity condition, a cost that tended to increase with age, showing the largest size in adults. This cost, as can be seen from their data report, was substantially due to a constant decrease in latencies in the identity priming condition. That is, latencies in this conditions decreased, showing that with the increase in reading experience participants became faster and faster. But this pattern was not apparent in the TL condition. In contrast, in the present data, the latencies for TLs decreased from the third-graders to the adults, as shown in Figure 1. How can these different results be reconciled?

The most apparent difference between the Kezilas et al' (2016) study and the present one is in the language, with Italian being highly transparent, compared to English. Italian children are more likely to use phonological recoding procedures at the beginning, but it is also well established that reading in Italian involves lexical processes as well, from the very early stages of reading development (Peressotti et al., 2010; Sulpizio & Colombo, 2013; Zoccolotti et al., 2009). English children may be more prone to rely on orthographic processes since the beginning, and therefore to immediately show TL priming effects. Italian children learn to read by the end of the first year, given the transparency of the language, while English-speaking children' reading ability is delayed

(Seymour, Aro, Erskin, 2003). A similar interpretation based on orthographic transparency was also proposed by Lété and Fayol (2013) who investigated TL effects in French. Their results are more difficult to directly compare to ours, because they measured the TL condition with one RL condition in which only one letter was replaced, and one control condition in which all letters were different. Nonetheless, they found facilitation for both the RL and for the TL conditions compared to the control condition in fifth-, but not in third-graders. As the authors suggested, although French is less regular than Italian, "French beginning readers tend to use a grapheme-to-phoneme coding strategy to encode words. A more direct lexical access process starts to become more prominent during the early phases of reading acquisition". (Leté & Fayol, 2013, p. 58). A similar trend was also reported by Ziegler et al. (2014) who also investigated TL priming effects with French speaking participants. Thus, diverging results may be (partly) explained as due to cross-linguistic differences in orthographic transparency. Readers of less transparent languages, in which whole word teaching methods may be more frequently used, show an earlier neglect of the letters position information, which tends to remain constant. Instead, readers of more regular languages tend to show more robust TL effect in later grades, and these tend to increase with reading experience.

In conclusion, our results suggest that Italian children's developmental trend in reading shows evidence for a very early use of phonological procedures, which are most convenient in a regular language, and do not allow TL priming effect to emerge clearly. After this first stage, very soon reading processes are likely to shift to orthographic processes that become optimal in adulthood, and allow letter position information to be less precisely coded, in order to trade off precision with reading speed.

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References.

Acha, J., & Perea, M. (2008). The effects of length and transposed letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology, 99*, 245-264.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-Effects Modeling with Crossed Random Effects for Subjects and Items. *Journal of Memory and Language*, 59, 390-412. http://dx.doi.org/10.1016/j.jml.2007.12.005

Bertinetto, P. M. Burani, C., Laudanna, A., Marconi, L., Ratti, D., Rolando, C., & Thorton, A. M. (2005). Corpus e Lessico di frequenza dell'italiano scritto (CoLFIS) [CoLFIS. Corpus and frequency lexicon of written Italian]. Retrieved from http://www.istc.cnr.it/material/database/colfis/index_eng.shtml

Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, *97*(3), 165-182.

Colombo, L., Sulpizio, S., & Peressotti, F. (2017). Serial mechanism in transposed letters effects: A developmental study. *Journal of Experimental Child Psychology*, *161*, 46-62.

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, *117*, 713-758.

Eddy, M. D., Grainger, J., Holcomb, P. J., & Gabrieli, J. D. (2016). Orthographic and phonological processing in developing readers revealed by ERPs. *Psychophysiology*, *53*, 1776-1783.

Faust, M. E., Balota, D. A., Spieler, D. H., & Ferraro, F. R. (1999). Individual differences in information-processing rate and amount: Implications for group differences in response latency. *Psychological Bulletin, 125*, 777-799.

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 39, 211-251.

Grainger, J. (2008). Cracking the orthographic code: An introduction. *Language and Cognitive Processes*, *23*, 1-35.

Grainger, J., Dufau, S., & Ziegler, J. C. (2016). A vision of reading. *Trends in Cognitive Sciences, 20*, 171-179.

Grainger, J., Lété, B., Bertand, D., Dufau, S., & Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition, 123,* 280-292.

Jaeger, T.F. (2008) Categorical Data Analysis: Away from ANOVAs (Transformation or Not) and towards Logit Mixed Models. *Journal of Memory and Language*, 59, 434-446. http://dx.doi.org/10.1016/j.jml.2007.11.007

Kezilas, Y., McKague, M., Kohnen, S., Badcock, N. A., & Castles, A. (2017). Disentangling the developmental trajectories of letter position and letter identity coding using masked priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*, 250-254.

Ktori, M., Kingma, B., Hannagan, T., Holcomb, P. J., & Grainger, J. (2014). On the time-course of adjacent and non-adjacent transposed-letter priming. *Journal of Cognitive Psychology*, *26*, 491-505.

Lété, B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked priming paradigm with French developing readers and dyslexics. *Journal of Experimental Child Psychology, 114*, 47-62

Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: A method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(3), 618.

Lupker, S. J., Perea, M., & Davis, C. J. (2008). Transposed-letter effects: Consonants, vowels and letter frequency. *Language and Cognitive Processes*, *23*(1), 93-116.

O'Connor, R. E., & Forster, K. I. (1981). Criterion bias and search sequence bias in word recognition. *Memory & Cognition*, *9*, 78-92.

Marconi, L., Ott, M., Pesenti, E., Ratti, D., & Tavella, M. (1994). *Lessico elementare: Dati statistici sull'italiano letto e scritto dai bambini delle elementari.* Bologna, Italy: Zanichelli.

Marelli, M., & Baroni, M. (2015). Affixation in semantic space: Modeling morpheme meanings with compositional distributional semantics. *Psychological Review, 122*, 485.

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language* 94, 305-315

Marelli, M., Amenta, S., Morone, E. A., & Crepaldi, D. (2013). Meaning is in the beholder's eye: Morpho-semantic effects in masked priming. *Psychonomic Bulletin & Review, 20*, 534-541.

Perea, M., & Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain and Language*, 97, 102–109.

Perea, M., & Lupker, S. J. (2003a). Does jugde activate COURT? Transposed-letter similarity effects in masked associative priming. *Memory & Cognition*, 31, 829-841.

Perea, M., & Lupker, S. J. (2003b). Transposed-letter confusability effects in masked form priming. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming: State of the art* (pp. 97-120). Hove, UK: Psychology Press.

Perea, M., & Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language*, *51*, 231-246.

Peressotti, F., Mulatti, C., & Job, R. (2010). The development of lexical representations: Evidence from the position of the diverging letter effect. *Journal of Experimental Child Psychology*, *106*, 177-183.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7(1), 65–81. doi:10.1016/0010-0285(75)90005-5

Sartori, G., Job, R., & Tressoldi, P. E. (1995). *The battery for evaluating dyslexia and dysorthography*. *Firenze: Edizioni OS.*

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes, 19*, 333-367.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition*, *55*, 151-218.

Seymour, P. H. K., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology*, 94, 143–174.

Sulpizio, S., & Colombo, L. (2013). Lexical stress, frequency, and stress neighbourhood effects in the early stages of Italian reading development. *The Quarterly Journal of Experimental Psychology*, *66*, 2073-2084.

Tiffin-Richards, S. P., & Schroeder, S. (2015). Children's and adults' parafoveal processes in German: Phonological and orthographic effects. *Journal of Cognitive Psychology, 27,* 531–548. http://dx.doi.org/10 .1080/20445911.2014.999076

Whitney, C. (2001). Position-specific effects within the SERIOL framework of letter-position coding. *Connection Science*, *13*, 235-255.

Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology*, 50, 1026–1036.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, 131, 3-29.

Zoccolotti, P., De Luca, M., Di Filippo, G., Judica, A., & Martelli, M. (2009). Reading development in an orthographically regular language: Effects of length, frequency, lexicality and global processing ability. *Reading and Writing, 22*, 1053-1079.

Table 1. Summary statistics: Means (and standard deviations) of orthographic neighborhood size (*Orthogr N-Size*), orthographic neighborhood frequency (*Orthogr N-Freq*) and bigram frequency for the four sets of primes used in the experiments.

	Transposed letters		Replaced letters	
	Inital	Final	Initial	Final
Orthogr N-Size	0.05 (0.21)	0.15 (0.51)	0.14 (0.40)	0.1 (0.33)
Orthogr N-Freq	0.39 (3.10)	1.01 (6.59)	0.36 (2.88)	0.88 (5.89)
Bigram Frequency	11.04 (0.50)	11.002 (0.44)	11.01 (0.57)	10.94 (0.55)

Note. The n size is calculated as the number of words that are obtained by changing the target's letters one at a time. The n frequency is calculated as the summed neighbors' frequency (Wagenmakers & Raaijmakers, 2006). Bigram frequency is log transformed on the basis of the natural logarithm.

Table 2. Mean percentages of accuracy (and standard deviation) by condition and priming effect (RL –TL conditions) for each group.

	TL -Initial	RL -Initial	Priming	TL -Final	RL -Final	Priming
2nd gr.	92.96 (25.58)	93.21 (25.16)	.25	92.72 (25.98)	91.39 (28.06)	-1.33
3rd gr.	96.42 (18.59)	93.89 (23.96)	-2.53	95.15 (21.48)	96.00 (19.61)	.85
5th gr.	97.12 (16.72)	96.75 (17.74)	-.37	96.87 (17.41)	95.62 (20.46)	-1.25
Adults	97.80 (14.68)	92.20 (26.84)	-5.6	98.00 (14.01)	92.20 (26.84)	-5.8

Table 3. Mean RTs (and standard deviations) for correct responses by condition and priming effect (RL –TL conditions) in ms.

	TL -Initial	RL -Initial	Priming	TL -Final	RL -Final	Priming
2nd gr.	2422 (917)	2393 (897)	29	2437 (932)	2464 (852)	27
3rd gr.	1895 (730)	1918 (706)	-23	1866 (697)	1896 (698)	-30
5th gr.	1229 (624)	1315 (634)	-86	1194 (568)	1305 (612)	-111
Adults	534 (106)	589 (118)	55	533 (110)	598 (126)	-65

Figure 1. Mean z-RTs for target words in the transposed letters (TL) and replaced letters (RL) conditions for the different groups.

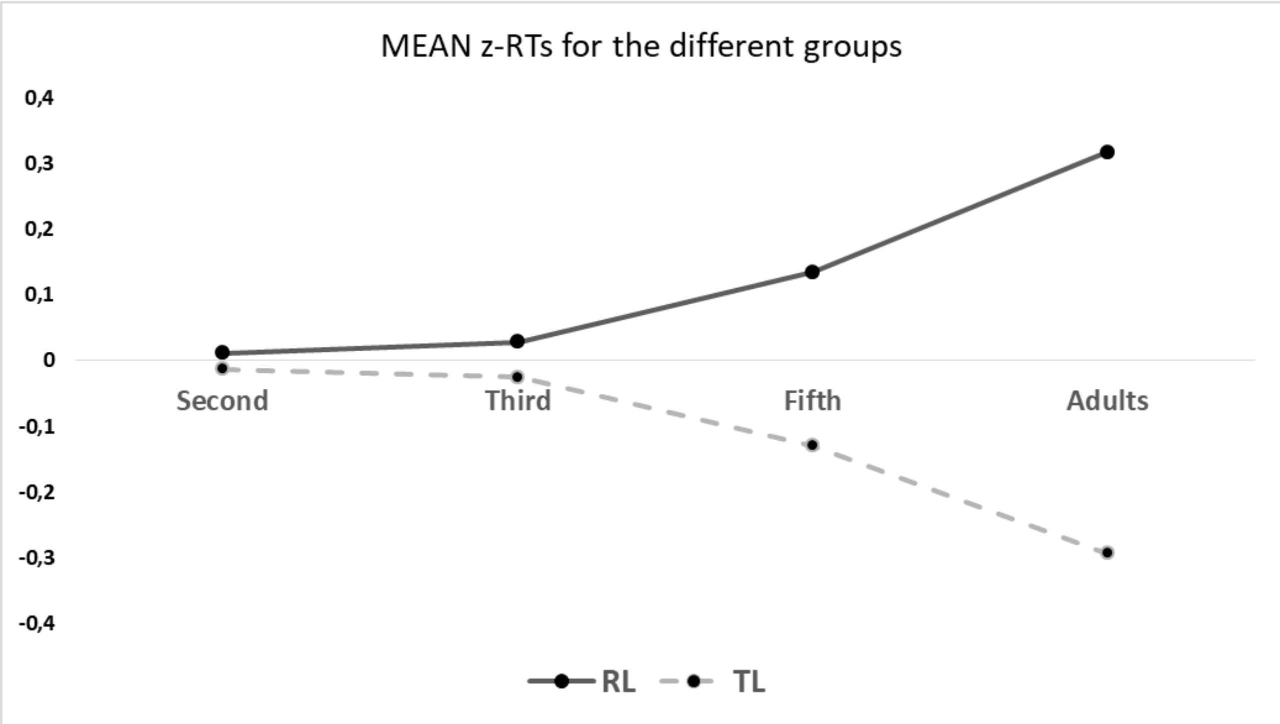
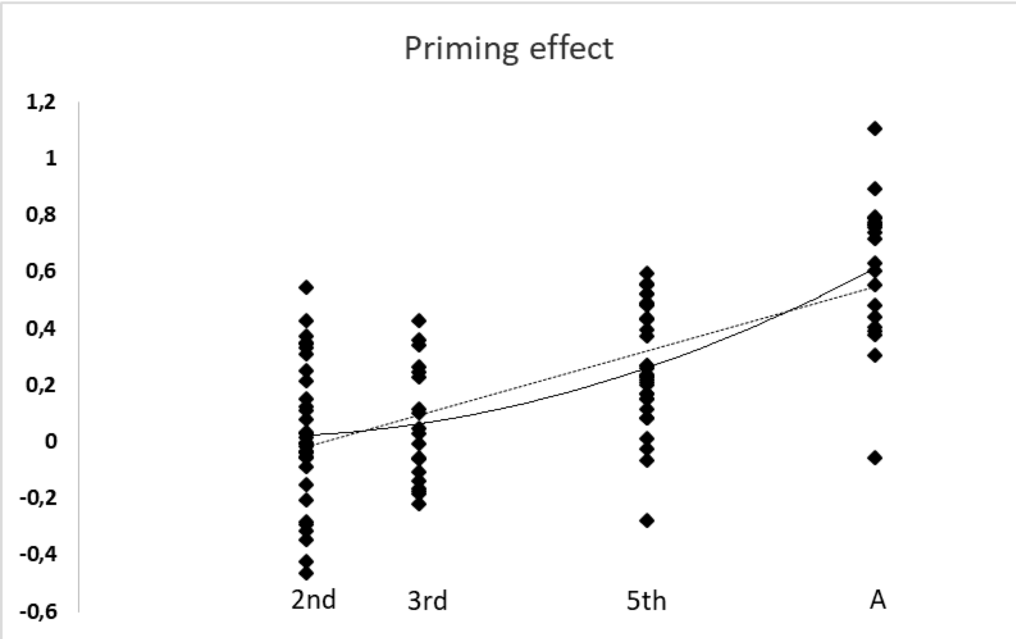


Figure 2. Size of the priming effect calculated as the difference between the TL and the RL z-scores for latencies, for second-, third-, fifth-graders and adults (2^{nd}, 3^{rd}, 5^{th}, A, respectively). The line shows the linear and the quadratic term of the regression.



Appendix.

N item	Target word	transposed_1	transposed_2	replaced_1	replaced_2
1	albergo	ablergo	albegro	acmergo	albetno
2	alfabeto	aflabeto	alfabteo	apnabeto	alfabuzo
3	ambiente	abmiente	ambinete	adniente	ambierle
4	arbitro	abritro	arbirto	acsitro	arbilfo
5	argento	agrento	argetno	aplento	argezbo
6	armadio	amradio	armaido	ansadio	armovio
7	armatura	amratura	armautra	avnatura	armatifa
8	artista	atrista	artitsa	alsista	artibna
9	asfalto	afsalto	asfatlo	adnalto	asfacmo
10	bambino	bmabino	bambnio	bicbino	bambeco
11	bilancia	bliancia	bilanica	bnuancia	bilanpia
12	braccio	barccio	bracico	bpoccio	bracpao
13	cantante	cnatante	cantnate	caplante	cantacle
14	colombo	cloombo	colobmo	cofembo	colopno
15	confetto	cnofetto	confteto	cupfetto	confubto
16	conquista	cnoquista	conqusita	cbaquista	conquicna
17	coperta	cpoerta	copetra	cinerta	copesga
18	cravatta	carvatta	cravtata	ctovatta	cravogta
19	dentista	dnetista	dentsita	deldista	dentizra
20	discorso	dsicorso	discroso	dibrorso	discofno
21	elefante	eelfante	elefnate	edofante	elefamce
22	entrata	etnrata	entrtaa	eclrata	entuba
23	esperto	epserto	espetro	ebnerto	especlo
24	estate	etsate	esttae	epmate	esufe
25	esterno	etserno	estenro	efberno	estedpo
26	fantasma	fnatasma	fantsama	fadmasma	fantacla
27	foresta	froesta	foretsa	fapesta	forebla
28	formica	fromica	formcia	fismica	formuza
29	freccia	ferccia	frecica	fmaccia	frecroa
30	furfante	fufrante	furfatne	fulbante	furfagle
31	gallina	glalina	gallnia	goplina	galleba
32	gigante	ggiante	gigatne	gopante	gigalde
33	graffio	garffio	grafifo	gboffio	grafgao
34	impronta	ipmronta	imprnota	idlronta	improcsa
35	incendio	inecndio	incenido	iglendio	incerpio
36	incontro	icnontro	inconrto	iflontro	inconlco
37	incrocio	icnrocio	incroico	iplrocio	incrobuo
38	indiano	idniano	indinao	ipmiano	indiubo
39	inferno	ifnerno	infenro	iplerno	infedpo

40	infinito	inifnito	infiinto	imlinito	infinero
41	influenza	ifnluenza	influneza	itbluenza	influebta
42	insalata	isnalata	insaalta	irlalata	insacuta
43	intanto	itnanto	intatno	iclanto	intapso
44	interno	itnerno	intenro	izlerno	intemco
45	intorno	itnorno	intonro	ivlorno	intovlo
46	inverno	ivnerno	invenro	idlerno	inveblo
47	istante	itsante	istatne	idvante	istafpe
48	istituto	itsituto	istiutto	ibrituto	istiteco
49	leggenda	lgegenda	leggneda	largenda	leggelta
50	leopardo	lepoardo	leopadro	leifardo	leopatso
51	letargo	lteargo	letagro	ludargo	letacdo
52	locanda	lcoanda	locadna	lobunda	locamra
53	mandorla	madnorla	mandlora	matcorla	mandofsa
54	mercato	mrecato	merctao	mupcato	mercufo
55	merenda	mreenda	meredna	mufenda	merelba
56	mistero	msitero	mistreo	moztero	mistomo
57	morbido	mrobido	morbdio	menbido	morbazo
58	orchestra	orhcestra	orchesrta	orbdestra	orchesdna
59	ospedale	opsedale	ospeadle	obredale	ospedife
60	padrone	pdarone	padrnoe	petrone	padrase
61	pantera	pnatera	pantrea	peftera	pantoba
62	paziente	pzaiente	pazinete	piliente	paziebre
63	pensiero	pnesiero	pensireo	paftiero	pensiuvo
64	petrolio	pertolio	petroilo	pofrolio	petroguo
65	pianura	pinaura	pianrua	puonura	pianiba
66	pinguino	pignuino	pingunio	pulguino	pinguofo
67	pistola	psitola	pistloa	poftola	pistefa
68	plastica	palstica	plasitca	pmostica	plasmoca
69	polenta	ploenta	poletna	pudenta	polemba
70	potente	ptoente	potetne	pifente	potelde
71	presepe	persepe	prespee	plasepe	presove
72	principe	pirncipe	prinicpe	pduncipe	printepe
73	pulsante	plusante	pulsnate	purmante	pulsafpe
74	puntura	pnutura	puntrua	piftura	puntoba
75	quaranta	quraanta	quaratna	quobanta	quaralca
76	racconto	rcaconto	raccnoto	rutconto	raccompo
77	ricordo	rciordo	ricodro	rezordo	riconbo
78	risposta	rsiposta	rispsota	ricrosta	rispomba
79	ritorno	rtiorno	ritonro	rovorno	ritoflo
80	robusto	rbousto	robutso	renusto	roburdo
81	romanzo	rmoanzo	romazno	rofunzo	romacfo
82	rondine	rnodine	rondnie	ribdine	rondoze

83	rotondo	rtoondo	rotodno	rulondo	rotolbo
84	scatola	sactola	scatloa	sogtola	scatiba
85	scultura	sucltura	scultrua	sebltura	scultoza
86	sdraiato	srdaiato	sdraitao	sfbaiato	sdraiuvo
87	seguente	sgeuente	segunete	sabuente	seguesce
88	serpente	seprente	serpetne	sembente	serpeble
89	spirito	siprito	spirtio	sburito	spirozo
90	stomaco	sotmaco	stomcao	sifmaco	stomipo
91	strumento	srtumento	struemnto	sblumento	strumepco
92	struzzo	srtuzzo	strzuzo	sfbuzzo	stripzo
93	talento	tlaento	taletno	tuvento	talebco
94	tedesco	tdeesco	tedecso	tilesco	tedefbo
95	tramonto	trmaonto	tramnoto	trifonto	tramobro
96	tremendo	termendo	tremnedo	tvomendo	tremebso
97	turista	truista	turitsa	tamista	turilca
98	ubriaco	urbiaco	ubricao	ulpiaco	ubriubo
99	vacanza	vcaanza	vacazna	vomanza	vacafla
100	verdura	vredura	verdrua	vusdura	verdoca