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Disentangling the Developmental Trajectories of Letter Position and Letter Identity Coding Using Masked Priming

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Masked transposed-letter (TL) priming effects have been used to index letter position processing over the course of reading development. Whereas some studies have reported an increase in TL priming over development, others have reported a decrease. These findings have led to the development of 2 somewhat contradictory accounts of letter position development: the lexical tuning hypothesis and the multiple-route model. One factor that may be contributing to these discrepancies is the use of baseline primes that substitute letters in the target word, which may confound the effect of changes in letter position processing over development with those of letter identity. The present study included an identity prime (e.g., listen—LISTEN), in addition to the standard two-substituted-letter (2SL; e.g., lidfen—LISTEN) and all-letter-different (ALD; e.g., rodfup—LISTEN) baselines, to remove the potential confound between letter position and letter identity information in determining the effect of the TL prime. Priming effects were measured in a lexical decision task administered to children aged 7–12 and a group of university students. Using inverse transformed response times, targets preceded by a TL prime were responded to significantly faster than those preceded by 2SL and ALD primes, and priming remained stable across development. In contrast, targets preceded by a TL prime were responded to significantly slower than those preceded by an ID prime, and this reaction-time cost increased significantly over development, with adults showing the largest cost. These findings are consistent with a lexical tuning account of letter position development, and are inconsistent with the multiple-route model.

Keywords: masked priming, lexical decision, letter position and identity coding, multiple-route model of reading, lexical tuning hypothesis

The skilled adult reading system is typically sensitive enough to distinguish between anagrammatic words such as *pat*, *tap*, and *apt*, yet is also remakrably flexilbe, enalbing these srcambled wodrs to be copmrehended with apperantly litlte congitive effort (Rayner, White, Johnson, & Liversedge, 2006). Clear evidence for flexible letter position coding comes from studies with skilled adult readers, showing that responses to targets preceded by a masked transposed-letter (TL) nonword prime (e.g., litsen—LISTEN) are faster and more accurate than responses to targets preceded by a control prime that substitutes letters in the target rather than transposing them (e.g., lidfen—LISTEN; Kinoshita, Castles, & Davis, 2009; Lupker & Davis, 2009; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003; Perea & Lupker, 2004).

A critical unresolved question is whether flexible letter position coding is a stable feature of the reading system or whether it changes across development. Developmental studies using the masked priming paradigm have produced conflicting findings. Although some studies have shown that the magnitude of TL priming increases with age, indicating that letter position coding becomes more flexible with development (Ziegler, Bertrand, Lété, & Grainger, 2013), others have shown that TL priming decreases with age, indicating that letter position coding becomes less flexible with development (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007).

These contrasting findings have been interpreted within the context of two alternative accounts of letter position development—the *multiple-route model of reading* (Grainger & Ziegler, 2011) and the *lexical tuning hypothesis* (Castles et al., 2007). According to the multiple-route model, beginning readers adopt a sequential grapheme-to-phoneme phonological recoding strategy, which is highly sensitive to the position of letters within words. As orthographic knowledge develops, the sequential strategy is re-

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placed by a specialized parallel letter processing system, which prioritizes rapid word retrieval over precise letter position processing, reflecting an increasingly coarse encoding of letter position information as reading develops. In contrast, the lexical tuning hypothesis proposes that early in reading development, the visual word recognition system can afford to be somewhat lax in regard to the exact coding of letter identity and position. As a reader's sight-word vocabulary grows, the visual word recognition system must tighten its input criterion to minimize potential confusion between visually similar words (e.g., *pat*, *tap*, *apt*, *pit*, *put*, *pal*), reflecting an increasingly precise encoding of both letter identity and position information with development.

In the present study, we propose that resolving the mixed findings within the literature, and distinguishing between these two accounts of letter position development, requires rethinking the use of the traditional substitution baseline primes used to measure the TL priming effect. In what follows, we outline the interpretative complications associated with using substitution baseline primes in developmental research, and advocate that the influence of the TL prime be measured as a cost relative to a prime that is an exact match to the target (e.g., litsen—LISTEN vs. listen—LISTEN).

The two baseline primes most commonly used to determine the effect of letter transpositions on target recognition in the masked priming literature are the two-substituted-letter (2SL) prime (e.g., lidfen—LISTEN), formed by substituting two letters in the same positions as the transposed letters in the TL prime (e.g., Lupker et al., 2008; Perea & Lupker, 2003, 2004), and the all-letter-different (ALD) prime (e.g., rodfup—LISTEN), formed by substituting all letters in the target (e.g., Andrews & Lo, 2012; Castles et al., 2007; Kinoshita et al., 2009). There is an implicit assumption within the literature that these baselines provide an equivalent reference point against which to measure the effect of the TL prime. As such, the facilitatory TL priming effects reported in these studies have been interpreted similarly, with larger facilitatory effects of the TL prime relative to the baseline indicating coarser coding of letter position.

However, studies with skilled adult readers including both baseline conditions indicate that a degree of caution should be used when comparing TL effects measured using a 2SL baseline with those using an ALD baseline. A recent mega study by Adelman et al. (2014) reported that the TL priming effect in skilled adult readers was smaller when measured against the 2SL prime compared with when the effect was measured against the ALD prime (see also Humphreys, Evett, & Quinlan, 1990, Experiment 2b, for a similar finding using the four-field priming paradigm). This finding suggests that the magnitude of the TL priming effect relative to the ALD baseline is not only influenced by the transposition manipulation but also by the fact that the untransposed letters within the TL prime are shared with the target (e.g., ***li***ts***en*** – ***LI***ST***EN***; ***rodf*****up** – ***LI***ST***EN***). As such, reports of a change across development in the magnitude of the TL priming effect relative to an ALD baseline (e.g., Castles et al., 2007; Lété & Fayol, 2013) are difficult to interpret, as the change could be driven, at least in part, by the shared letter identities between the TL prime and the target.

Measuring the TL prime against a 2SL baseline obviates this problem, as the unmanipulated letters in both the TL and 2SL prime match their corresponding letters in the target (e.g., ***li***ts***en*** – ***LI***ST***EN***; ***li***df**en** – ***LI***ST***EN***). However, the TL-2SL priming effect comes with its own interpretative problems. Because it is unclear how the developing system processes primes that substitute two letters in the target, it is also unclear as to what is driving the reported changes in TL priming effects measured against the 2SL baseline. Indeed, a change in priming could be driven by a change in sensitivity to the transposition manipulation within the TL prime, a change in sensitivity to the substitution manipulation within the 2SL prime, or by a complex interaction between the two.

The potential confound between letter identity and letter position information also means that the TL-2SL priming effect is unable to adequately distinguish between the multiple-route model of reading (Grainger & Ziegler, 2011) and the lexical tuning hypothesis (Castles et al., 2007). Reports of an increase across development in the TL-2SL priming effect have been taken as evidence in support for the multiple-route model and against the lexical tuning hypothesis: Older readers process letter position more coarsely than younger readers, resulting in a larger facilitatory effect of the TL prime (e.g., Ziegler et al., 2013). However, these findings can also be explained within a lexical tuning framework, by assuming that the tuning of letter position develops more gradually than the tuning of letter identity (Castles et al., 2007). According to this account, early in reading development the TL and 2SL primes may facilitate target word recognition to a similar degree. As the visual word recognition system becomes tuned to letter identity and position, it becomes less tolerant to the TL and 2SL manipulations, resulting in both primes having less influence over target word recognition. However, if it is the case that precise letter position coding develops more gradually than precise letter identity coding, as has been suggested by Castles et al. (2007), then the TL prime will facilitate target word recognition more so than the 2SL prime, resulting in a larger TL-2SL priming effect for older readers than for younger readers.

Discriminating between these conflicting accounts of letter position development therefore requires that the TL priming effect be measured against a baseline that does not confound letter position with letter identity effects. As suggested by Kinoshita et al. (2009), one way to achieve an unambiguous measure of the effect of the transposition manipulation is to compare the TL prime with an identity (ID) prime that is an exact match to the target (e.g., listen—LISTEN). The advantage of this comparison is that both the TL and ID primes share all letter identities with the target and differ only in the position of the letters. Measured this way, the magnitude of the difference between the TL and ID conditions reflects the cost of the transposition manipulation, and so provides an index of the precision in the coding of letter position information (i.e., less tolerance to the TL manipulation), reversing the facilitation logic of the more standard comparison of the TL prime against substitution controls.

To our knowledge, the TL cost relative to the ID baseline has not yet been investigated using the masked primed lexical decision paradigm with developing readers. It has, however, been investigated with German children (mean age = 8.46 years, $SD = 0.59$) and adults using the boundary eye tracking method during sentence reading in a recent study by Tiffin-Richards and Schroeder (2015). The authors presented target words within a sentence following previews that were either identical to the target (e.g., Rand—Rand), transposed two letters within the target (e.g., Rand—Rnad), or substituted two letters in the target (e.g., Rand—Rcod). The TL preview effect was measured both as an advantage relative to the 2SL preview as well as a cost relative to the ID preview. The results were most consistent with the predictions of the multiple-route model. Specifically, the TL cost (for internal transposition manipulations) was smaller for adults than for children. In addition, adults showed a clear TL preview advantage for internal transposition manipulations relative to the 2SL preview, whereas children did not. Whether these findings generalize to English readers, and to single word paradigms such as the masked primed lexical decision task, remains to be seen.

The Present Study

The aim of the present study was to investigate the development of letter position coding in English readers using the masked priming technique, and to determine whether the pattern of results is contingent on the baseline prime used to measure the TL priming effect. Four developmental groups were included in the study—children in early primary school (Grades 2 and 3), middle primary school (Grade 4), late primary school (Grades 5 and 6) and university students. The TL priming effect was measured against three baselines—2SL, ALD, and ID. To ensure that the priming effects were comparable across developmental groups, the main analyses were based on inverse transformed data, and when appropriate, interaction effects were confirmed with additional analyses on Z-transformed data (see Acha & Perea, 2008; Faust, Balota, Spieler, & Ferraro, 1999; Lété & Fayol, 2013; Ziegler et al., 2013 for a similar approach).

We first report the TL priming effects as measured against the traditional 2SL and ALD baseline conditions. Considering the limitations of these comparisons as outlined in the previous section, we had no clear, theory-driven predictions regarding the developmental trajectory of these effects. However, if it is the case that the development of the TL-ALD priming effect is driven in part by the shared letters between the TL prime and the target, it is possible that the pattern of priming across development may differ for the TL-2SL and TL-ALD comparisons. To the best of our knowledge, this is the first developmental study to measure TL priming against both 2SL and ALD baselines—an important contribution given the mixed findings within the literature using these two baselines.

Of most interest to the present study was the developmental trajectory of the TL priming cost relative to the ID baseline. This comparison enables us to test two clearly contrasting theoretical predictions. If it is the case that letter position is encoded more precisely with development, as proposed by the lexical tuning hypothesis, the TL cost should increase across the four developmental groups, indicating that the visual word recognition system becomes less tolerant to manipulations of letter position. In contrast, if letter position is encoded more coarsely with development, as proposed by the multiple-route model, the TL cost should decrease across the four groups, indicating that the system becomes more tolerant to manipulations of letter position.

Method

Participants

Eighty-two children from Grades 2 to 6 were tested during the first semester of the school year. The children were tested as part of a research holiday program at Macquarie University. Children received a small monetary reward for their participation. The adult sample consisted of 40 undergraduate students from Macquarie University who participated in the study in exchange for course credit. All participants were native speakers of English. Further information about participants is detailed in Table 1.

Materials

The task consisted of 72 word targets and 72 nonword targets, which were five and six letters in length ($M = 5.64$, $SD = 0.48$). Word targets were selected from the Oxford Wordlist (Bianco, Scull, & Ives, 2008) to be known by children in Grade 1. All words except for one were also included in the Children's Printed Word Database (Masterson, Stuart, Dixon, & Lovejoy, 2003). On average, target words had a CELEX written word frequency of 259.81 per million ($SD = 351.77$), and a neighborhood density of 2.53 ($SD = 2.86$) using Coltheart's N (Coltheart, Davelaar, Jonasson, & Besner, 1977). Each word target was paired with four primes, including a TL prime (e.g., litsen—LISTEN), a 2SL prime (e.g., lidfen—LISTEN), an ALD prime (e.g., rodfup—LISTEN), and an ID prime (e.g., listen—LISTEN). The TL and 2SL primes were created by changing two internal consonants within the target word. Fifty-eight of the 72 items involved changing adjacent consonants, and 14 involved changing nonadjacent consonants. The 2SL prime was matched to the TL prime by substituting letters of the target at the same letter positions that were transposed in the TL prime. To ensure comparability of the 2SL and ALD conditions, the two substituted letters in the 2SL prime were carried over to the ALD prime in the same positions, and all remaining letters in the target were then substituted (vowels for vowels and consonants for consonants). TL, 2SL, and ALD primes were matched as closely as possible on Coltheart's N (TL, $M = 0.32$, $SD = 0.71$; 2SL, $M = 0.26$, $SD = 0.58$; ALD, $M = 0.10$, $SD = 0.30$), with most primes having no neighbours (range = 0–3). The frequency and neighborhood density estimates were obtained using N-Watch (Davis, 2005).

Nonword targets were created by replacing at least two letters of each target word, such that nonword and word targets were matched on CV structure. Each nonword target was paired with a TL prime, a 2SL prime, an ALD prime, and an ID prime. Primes were created for the nonword targets in the same way as described for word targets. Stimuli are reported in the Appendix.

Procedure

The lexical decision task was run using DMDX (Forster & Forster, 2003). The two-alternative-forced-choice responses were made using an external button box, recording response times (RTs) and accuracy. On each trial, a string of hashmarks the same length

Table 1
N, Gender, and Age of Participants in Each Grade Level

Grade	*n*	Gender (female)	Age
2	15	6	7y, 8m (5m)
3	12	6	8y, 6m (4m)
4	25	11	9y, 5m (4m)
5	14	7	10y, 7m (4m)
6	16	5	11y, 7m (5m)
University	40	35	23y, 2m (8y, 5m)

Note. Numbers in parentheses denote the standard deviation of the mean. y = years; m = months.

as the prime and target was presented for 500 ms, followed by the prime in lowercase for 50 ms (five ticks, 10.01 ms per tick), followed by the target. The target remained on the screen for a maximum of 10 s or until the participant made a response. Participants were encouraged to respond as accurately and as quickly as possible. Children were given additional instructions using flash cards prior to the task to ensure they understood the requirements. The experiment started with a practice block of 16 items, followed by six blocks of 24 items (six items per priming condition in each block, half words and half nonwords), including two buffer items at the beginning of each block, which were not included in the analysis. Four counterbalanced lists of the task were created such that each target appeared in each priming condition across lists. Each participant was assigned a single list such that they saw each target only once. Trial presentation was randomized within each experimental block, and the order of block presentation was also randomized.

Results

One target word was removed from the analyses because of the accidental inclusion of a TL word prime instead of a nonword prime (tyring—TRYING). Four subjects (three in Grade 2, one in Grade 3) who made 40% or more errors on the lexical decision task were removed from the analyses. Following this, four words and six nonwords were removed from the analyses, as they elicited more than 40% errors from the remaining participants in any one grade level. All trials with RTs less than 150 ms were also removed (<1% of the remaining data). Trials with RTs greater than three standard deviations above the participants' grand mean RT (as calculated on all remaining trials) were then removed to reduce the effect of outliers (<2% of the remaining data: Grade 2 = 1.89%, Grade 3 = 1.71%, Grade 4 = 2.17%, Grade 5 = 1.77%, Grade 6 = 2.02%, university = 1.84%). Only correct responses were analyzed in the RT analyses.

Because there were too few participants in some grade levels, we were unable to include grade level reliably in the analyses. We therefore grouped participants into four developmental categories: early primary schoolers (Grades 2 and 3 combined, *N* = 23) middle primary schoolers (Grade 4, *N* = 25), late primary schoolers (Grades 5 and 6 combined, *N* = 30), and university students (*N* = 40). For ease of interpretation and comparison with previous studies, the analyses reported use these four groups to index reading development.

Observation of the RT data revealed large differences between groups in global response speed, which were likely exacerbated by longer RT tails for younger participants. Because differences in RT distributions between groups have been suggested to distort priming comparisons (Ziegler et al., 2013), RTs were inverse back-transformed (−1,000/RT) to normalize the data prior to analysis (see Figure 1, Panel A). Furthermore, wherever we found a significant Group × Condition interaction on the inverse RT data, we ran the same analysis except including Z-transformed RTs ([RT for accurate word trial – participant mean RT for accurate words]/standard deviation of the mean) as the dependent variable (see Figure 1, Panel B). This additional measure was taken to confirm that the main analyses were not confounded by differences between groups in global response speed (Faust et al., 1999). For comparison to previous studies that have reported analyses based on untransformed data, the raw RT

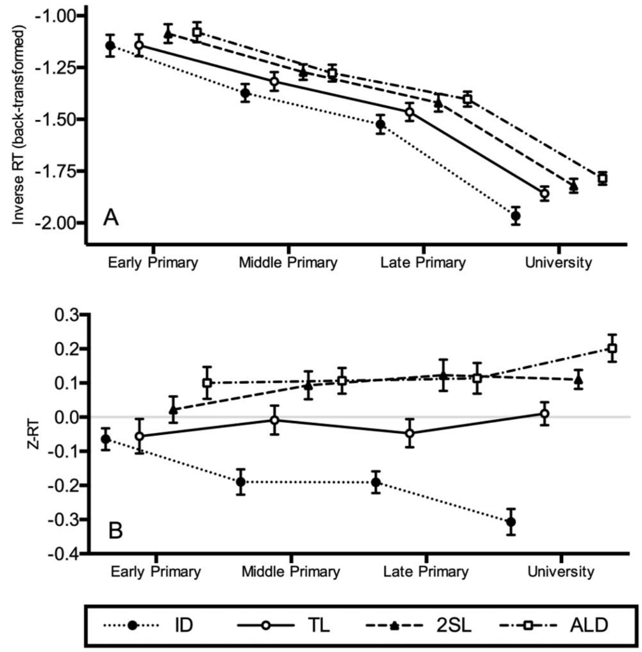

Figure 1. (A) Mean back-transformed inverse response times (RTs; −1,000/RT) to target words by condition and developmental group. Smaller inverse RTs indicate faster responses. Means are based on the subject data (mean RT was calculated for each subject for each condition prior to calculating the grand mean for each group for each condition). (B) Mean Z-RT for target words by condition and developmental group. Z-RT for each participant was calculated in the following way: ([raw RT for accurate word trial – participant mean raw RT for accurate words]/standard deviation of the mean). Mean Z-RT for each condition for each group was then calculated. Z-RTs less than zero reflect faster performance than the group's mean RT, and Z-RTs more than zero reflect slower performance than the group's mean RT. Error bars in both Panels A and B denote the standard error of the mean.

data are presented in Table 2, and the priming effects based on the raw RT data for target words is presented in Table 3.

Accuracy data and nonword data were not analyzed, as we had no clear predictions in regard to these effects. Nevertheless, the accuracy and nonword data are included in Table 2 for completeness. Observation of the RT data relative to the accuracy data revealed no evidence for a speed–accuracy trade-off.

Linear mixed effects modeling, as implemented in lme4 package (Bates, Maechler, Bolker, & Walker, 2015), formed the main analyses. Planned contrasts were conducted using lsmeans package (Lenth, 2015). Three separate analyses were performed for each priming effect of interest (TL-ALD; TL-2SL, TL-ID). For each analysis, we used competitive model testing to first settle on a general model, before undertaking more detailed analyses. Three models were considered:

1. a model including the main effect of condition,
2. a model including the main effect of condition and group, and
3. a model including the main effect of condition and group, as well as the interaction between the two.

Table 2
Accuracy (%) and RT (Ms) for Words and Nonwords by Prime Type and Developmental Group

Group	Dependent measure	Word				Nonword			
		ID	TL	2SL	ALD	ID	TL	2SL	ALD
Early primary	Accuracy (%)	92.47 (7.03)	89.59 (8.00)	89.52 (10.42)	90.19 (10.65)	86.72 (14.14)	88.30 (17.01)	84.40 (16.62)	86.53 (15.23)
	Raw RT (ms)	1052.54 (395.33)	1067.98 (526.34)	1079.59 (395.34)	1113.01 (425.38)	1303.22 (544.88)	1291.30 (596.16)	1263.02 (514.67)	1309.65 (547.81)
Middle primary	Accuracy (%)	92.01 (8.84)	94.27 (6.59)	89.82 (9.36)	92.20 (6.75)	90.41 (10.74)	92.51 (8.66)	88.63 (10.18)	90.75 (10.44)
	Raw RT (ms)	797.26 (153.61)	847.88 (201.05)	858.27 (160.77)	866.17 (161.33)	991.91 (279.63)	977.55 (212.73)	967.34 (253.25)	983.23 (238.61)
Late primary	Accuracy (%)	93.15 (6.59)	93.85 (7.16)	92.75 (6.78)	93.38 (6.15)	91.73 (8.29)	89.96 (12.71)	92.52 (8.00)	93.60 (6.58)
	Raw RT (ms)	721.01 (157.25)	746.73 (143.19)	791.66 (196.78)	773.95 (157.09)	865.47 (192.66)	884.19 (227.00)	861.67 (182.98)	871.50 (217.43)
University	Accuracy (%)	98.66 (2.53)	96.22 (4.81)	96.47 (4.39)	96.08 (5.20)	94.32 (9.79)	96.50 (8.40)	95.94 (7.59)	96.01 (5.98)
	Raw RT (ms)	535.34 (87.76)	563.46 (76.61)	572.79 (78.02)	580.77 (70.05)	695.35 (221.80)	677.36 (217.85)	682.27 (226.30)	695.79 (177.14)

Note. Numbers in parentheses denote the standard deviation of the mean. ID = identity prime; TL = transposed letter prime; 2SL = two-substituted-letter prime; ALD = all-letter-different prime.

Intercepts were allowed to vary by subjects and items. Models were compared pairwise in order of complexity. Model 1 was compared with an intercept-only model.

Planned contrasts were performed on the model that was most complex and provided a significantly better fit to the data than the simpler model it was compared with. Where the interaction model provided the best fit, we report the priming effect for each group, as well as all pairwise comparisons between the groups in the priming effect (low vs. middle primary, low vs. late primary, middle vs. late primary, low vs. university, middle vs. university, late vs. university). This was done to enable comparison with previous studies, which vary in the age range of participants tested (see Ziegler et al., 2013, for a discussion on how varying age groups might contribute to the mixed findings within the TL priming literature).

TL Priming Measured Against 2SL Baseline

Including the main effect of prime condition significantly improved the model fit (Model 1: $\chi^2[1] = 18.79$, $p < .0001$), as did including the main effect of group (Model 2; $\chi^2[3] = 119.28$, $p < .0001$). Including the interaction between condition and group did not significantly improve the fit (Model 3; $\chi^2[3] = .62$, $p = .893$). Participants were faster to respond to words preceded by a TL prime than to those preceded by a 2SL prime, and older participants were faster to respond than younger participants.

Table 3
Priming Effects (Ms) For Each Group Calculated From Mean RTs Presented in Table 2

Group	2SL-TL	ALD-TL	ID-TL
Early primary	11.61	45.03	−15.44
Middle primary	10.39	18.29	−50.62
Late primary	44.93	27.22	−25.72
University	9.33	17.31	−28.12

Note. 2SL-TL = raw RT for two-substituted-letter prime condition minus raw RT for transposed letter prime condition; ALD-TL = raw RT for all-letter-different prime condition minus raw RT for transposed letter prime condition; ID-TL = raw RT for identity prime condition minus raw RT for transposed letter prime condition. Positive numbers indicate a facilitatory effect of the TL prime relative to the baseline (2SL, ALD or ID), and negative numbers indicate a cost effect of the TL prime relative to the baseline.

TL Priming Measured Against ALD Baseline

Including the main effect of prime in the model significantly improved the fit (Model 1; $\chi^2[1] = 36.58$, $p < .0001$), as did including the main effect of group (Model 2; $\chi^2[3] = 118.47$, $p < .0001$). Including the interaction between the two did not significantly improve the fit (Model 3; $\chi^2[3] = .99$, $p = .805$). Responses to words preceded by a TL prime were significantly faster than those to words preceded by an ALD prime, and older participants responded more quickly than younger participants.

TL Priming Measured Against ID Baseline

Including the main effect of condition significantly improved the fit of the model (Model 1; $\chi^2[1] = 35.52$, $p < .0001$), as did including the main effect of group (Model 2; $\chi^2[3] = 115.50$, $p < .0001$), and the interaction between condition and group (Model 3; $\chi^2[3] = 12.58$, $p = .006$). The interaction between condition and group was also significant when Z-transformed RTs were included as the dependent variable in the model, $\chi^2(3) = 12.46$, $p = .006$, indicating that the interaction was not driven by a difference between groups in global response speed (see Faust et al., 1999).

Follow-up contrasts based on the interaction inverse RT model (Model 3) revealed that early primary schoolers showed no difference in RTs for the TL and ID prime conditions ($b < .01$, standard error [SE] = .03, $t = .03$, $p = .976$). All other groups showed a significant TL cost, responding slower to targets preceded by a TL prime than to those preceded by an ID prime (middle primary: $b = .05$, $SE = .02$, $t = 2.29$, $p = .022$; late primary: $b = .06$, $SE = .02$, $t = 2.89$, $p = .004$; university: $b = .11$, $SE = .02$, $t = 5.90$, $p < .0001$). Late primary schoolers showed a marginally larger cost effect than early primary schoolers ($b = .06$, $SE = .03$, $t = 1.91$, $p = .056$). University students showed a larger cost effect than early primary schoolers ($b = .11$, $SE = .03$, $t = 3.50$, $p = .0005$), and a marginally larger cost effect than middle primary schoolers ($b = .05$, $SE = .03$, $t = 1.78$, $p = .075$). No other contrasts approached significance (early vs. middle: $b = .06$, $SE = .03$, $t = 1.60$, $p = .110$; middle vs. late: $b = .01$, $SE = .03$, $t = .25$, $p = .801$; late vs. university: $b = .05$, $SE = .03$, $t = 1.60$, $p = .110$).

Discussion

The aim of the present study was to map the developmental trajectory of letter position coding in English readers using the masked priming paradigm, and to determine whether the pattern of results is influenced by the type of baseline prime used to measure the effect. To this end, we administered a masked TL priming task including three baseline primes—2SL, ALD and ID—to students in early primary school (Grades 2 and 3), middle primary school (Grade 4), late primary school (Grades 5 and 6), and at a university. The novel inclusion of the ID prime enabled us to investigate changes in sensitivity to the TL prime independently of letter identity effects, and hence enabled us to adjudicate between competing theories of letter position development. Participants were significantly faster to respond to target words preceded by a TL prime relative to those preceded by a 2SL and ALD prime, and the magnitude of these effects remained stable across development. In contrast, the TL cost effect gradually increased across development, with students in early primary school displaying no TL cost, and university students displaying the largest TL cost in the sample.

Although some studies have reported a decrease across development in the TL priming effect measured against a 2SL or ALD baseline (Acha & Perea, 2008; Castles et al., 2007), others have reported an increase in priming (Lété & Fayol, 2013; Ziegler et al., 2013). Our finding that TL priming relative to the traditional substitution controls remained stable across the four developmental groups therefore contributes a new finding to the series of contradictory results within the masked priming literature. Furthermore, that both the TL-2SL and TL-ALD priming effects remained stable over the course of development suggests that differences between studies in the type of substitution baseline prime used to measure the priming effect is unlikely to be contributing to the mixed findings.

The source of conflicting findings within the literature therefore remains unclear. As noted by Ziegler et al. (2013), differences between studies in data treatment prior to analysis might be one possible source. Although some studies have focused their analyses on raw (untransformed) RT data (e.g., Acha & Perea, 2008; Castles et al., 2007), others, including the present study, have analyzed transformed data (Ziegler et al., 2013). Whether RTs have been transformed prior to analysis can greatly influence the interpretation of the data (Ziegler et al., 2013). For example, although Ziegler et al. (2013) reported an increase across Grades 1 to 5 in the TL priming effect relative to the 2SL baseline, their untransformed data are more consistent with a decrease in priming, replicating Acha and Perea's (2008) untransformed RT data from children in Grades 2 and 4. Similarly, in the present study, we found no change across development in the TL priming effect relative to the ALD baseline, yet our untransformed data are comparable with Castles et al. (2007), who found a decrease in the TL-ALD priming effect with development (Castles et al.: Grade 3 = 64 ms, Grade 5 = 43 ms, adults = 8 ms; present study: early primary [Grades 2 and 3] = 45 ms, late primary [Grades 5 and 6] = 27 ms, adults = 17 ms).

The clear influence that data transformations can have on the pattern of priming across development suggests that the decision to transform RT data must be carefully considered prior to analysis. This issue has never been more relevant, with a growing number of psycholinguistic studies opting to use linear mixed effects modeling—a form of analysis that typically cannot be conducted reliably on raw RTs because of the inherent skew in RT data (Lo & Andrews, 2015). Aside from the fact that the linear mixed effects analyses in the present study required the data to be transformed, we had clear motivation to transform our data: Global response speed was considerably slower and more variable for children than for adults, and hence performing analyses on the untransformed data had potential to lead to spurious overadditive interactions (Faust et al., 1999; Ziegler et al., 2013). Both inverse RT transformations and Z-transformations, as used in the present study, have been used in previous research to make developmental groups more comparable with one another (e.g., Faust et al., 1999; Ziegler et al., 2013). In light of this, we argue that the transformed data offers the best representation of the pattern of priming effects observed across our four developmental groups, and we therefore join others in advocating the use of appropriately transformed RT data in developmental research (e.g., Faust et al., 1999; Lété & Fayol, 2013; Ziegler et al., 2013).

Of critical interest to the present study was the developmental trajectory of the TL cost relative to the ID prime. Because both TL and ID primes share all letter identities with the target and differ only in the position of the letters, the TL-ID comparison enables us to distinguish very clearly between the predictions of the multiple-route model and the lexical tuning hypothesis. The multiple-route model predicts that younger readers should show a significant TL cost because of their reliance on phonological recoding—a reading strategy that is highly sensitive to the position of letters within words. The TL cost should gradually decrease across development, reflecting a transition from phonological recoding to orthographic processing, which prioritizes fast and automatic word retrieval over precise letter position coding. In direct contrast, the lexical tuning hypothesis predicts that the visual word recognition system should be somewhat tolerant to letter position manipulations early in development, such that transposing two letters within the TL prime comes at no cost relative to a prime that is an exact match to the target (i.e., the ID prime). As sight word vocabulary develops, the system should tighten its input criterion to minimize competition between visually similar words, resulting in an increase in the TL cost across development. The finding that the TL cost relative to the ID prime increased across development, with the youngest group showing no TL cost and the eldest group showing the largest TL cost in the sample, is therefore consistent with the lexical tuning hypothesis and inconsistent with the multiple-route model account of letter position development. Whether the development of precise letter position coding is driven specifically by a growth in sight word vocabulary, or by other factors such as a general maturation of the visual system independently of lexical development (Gomez, Ratcliff, & Perea, 2008), requires further research.

The developmental trajectory of the TL-2SL priming effect, interpreted within the context of the TL-ID comparison, also has important implications for theories of letter position development. The youngest children in our sample showed no difference in RTs for the TL and ID prime conditions, yet showed significantly slower RTs to targets in the 2SL condition. This finding suggests that in comparison with letter position, letter identity information is coded relatively precisely in early primary school readers, such that the 2SL prime does not facilitate target recognition to the same degree as the TL and ID prime. From early primary school (Grades 2 and 3) onward, the system seems to consistently code letter identity information more precisely than letter position information, as is evidenced by the stable TL-2SL effect across the four developmental groups. Whether children in kindergarten and Grade 1 also show a TL-2SL effect cannot be determined based on the present set of results. Although speculative, it could be that letter identity information is coded just as coarsely as letter position information earlier in development, such that Grade 1 and kindergarten readers show no difference in RTs between the 2SL, TL, and ID conditions. This hypothetical finding, in conjunction with the results presented here, would join other studies in suggesting that the system becomes tuned to letter identity information earlier in development than letter position information (Castles et al., 2007; Kohnen & Castles, 2013).

The findings from the present study are in contrast to those reported by Tiffin-Richards and Schroeder (2015) using the boundary eye-tracking method during sentence reading in German. These authors found that the TL cost (longer fixation times for targets preceded by a TL preview that transposed two internal letters in the target, relative to those preceded by an ID preview) was larger for children than for adults, indicating that children code letter position more precisely than adults. Furthermore, unlike in the present study, children showed no clear TL preview advantage over the 2SL preview, suggesting that letter identity and position information are coded similarly in young readers. One possibility for this discrepancy is that children learning to read in a relatively shallow orthography, such as German, process letter position differently to those learning to read in a relatively dense orthography, such as English (see Frost, 2012, for a review of cross-language differences in letter position effects; see also Lété & Fayol, 2013). Differences between paradigms may also explain the conflicting findings—it could be that letter position is coded differently when words are presented in isolation, as in the present study, than when they are presented within a sentence and hence word recognition is supported by semantic context.

In sum, this article investigated the developmental trajectory of letter position coding in children aged 7 to 12 years and adults. The present study extended previous research by investigating the influence of the TL prime on target processing as a cost relative to an ID baseline. The key finding that the TL cost increased across development, such that students in early primary showed no TL cost, and those in university showed the largest cost in the sample, is consistent with the idea that letter position is coded more precisely as reading develops. Further research is needed to determine whether this developmental effect generalizes to different experimental paradigms and languages.

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Appendix

Word and Nonword Targets and Primes

Target	ID	TL	2SL	ALD	Target	ID	TL	2SL	ALD
				Word Targets and Primes					
ATLAS*	atlas	altas	abras	ibrun	LEDGE	ledge	legde	lefre	bifro
WORMS	worms	womrs	wonbs	finbl	WHALE	whale	wlahe	wrabe	trobi
EIGHT	eight	eihgt	eispt	oaspn	LUNCH	lunch	lucnh	lubsh	kibst
CLOSE	close	csole	cmobe	vmabi	WATCH	watch	wacth	wanph	minpk
WORLD	world	wolrd	wosfd	masfv	BIRDS	birds	bidrs	bimfs	numfz
THREE	three	trhee	tlbee	slboo	FIRST	first	fisrt	ficdt	nocdm
AFTER	after	atfer	akser	ukson	CELERY*	celery	cerely	cemeby	pomibt
OWNERS*	owners	onwers	ovbers	avbipz	BANGED	banged	bagned	balred	molrus
THIRTY	thirty	thitry	thikpy	slokpn	PACKET	packet	pakcet	pavbet	nivbor
TWELVE	twelve	twevle	twecke	bnicko	LOCKED	locked	lokced	lomfed	simfun
BUSHES	bushes	buhses	buvjes	movjid	LIGHTS	lights	lihgts	licfts	nocfnr
BARKED	barked	bakred	bagmed	nogmif	TRYING*	trying	tyring	tlping	slposh
NUMBER	number	nubmer	nujder	bojdip	MARKET	market	makret	mafget	lofgob
WIZARD	wizard	wirazd	winapd	fonupx	MASTER	master	matser	mabler	poblin
PICKED	picked	pikced	pixsed	nexson	OPENED	opened	oneped	ogebed	ugibur
BEHIND	behind	benihd	bekigd	lukogm	TURNED	turned	tunred	tupsed	bopsik
MOTHER	mother	mohter	mopger	yupgiv	JUMPED	jumped	jupmed	jugbed	pagbin
THINGS	things	thigns	thimbs	slambr	PEOPLE	people	peolpe	peogbe	maigbu
FIFTY	fifty	fitfy	fidby	nodbl	CHASE	chase	csahe	cnaqe	dniqu
WHOLE	whole	wlohe	wnobe	snubi	LUCKY	lucky	lukcy	lutmy	botmz
ANGRY	angry	anrgy	anwfy	ubwfl	THREW	threw	trhew	tdsew	bdsag
EARTH	earth	eatrh	eagph	oigpn	PARTY	party	patry	panby	gonbs
UNTIL*	until	utnil	ufgil	ofgep	EVERY	every	erevy	eteny	utonb
NIGHT	night	nihgt	nifct	vafcd	OTHER	other	ohter	olfer	alfud
ASKED	asked	aksed	apwed	opwib	EAGLES	eagles	ealges	eafhes	oifhuz
TYPING	typing	tpying	tlming	clmars	TWENTY	twenty	twetny	twevpy	brivpl
MEMORY	memory	meromy	mecoby	nicabp	CHURCH	church	chucrh	chubth	slibtn
KICKED	kicked	kikced	kipred	fopran	EXCEPT	except	ecxept	ebnept	abnirf
SUNDAY	sunday	sudnay	supqay	copqeb	LISTEN	listen	litsen	lidfen	rodfup
PERSON	person	pesron	peqmon	biqmud	ANIMAL	animal	aminal	atibal	utobeg
BOUGHT	bought	bouhgt	bourlt	nairld	CENTRE	centre	cetnre	cespre	mospbu
SECRET	secret	sercet	sevnet	livnob	FLYING	flying	fyling	frping	brpath
HUNGRY	hungry	hugnry	hubtry	sabtml	FAMILY	family	falimy	fagiby	dogabs
PLACES	places	pcales	phaves	thuvon	ALWAYS	always	awlays	agmays	igmudf
BEFORE	before	berofe	benole	junila	WANTED	wanted	watned	wacred	bocrul
SCHOOL	school	shcool	stmool	brneek	LITTLE	little	litlte	litbje	poddka

(*Appendix continues*)

Appendix (*continued*)

Target	ID	TL	2SL	ALD	Target	ID	TL	2SL	ALD
				Nonword Targets and Primes					
IMCUN	imcun	icmun	ikdun	akdob	BENGE	benge	begne	bewhe	diwho
ZORTS	zorts	zotrs	zopjs	mipjb	THAGE	thage	tgahe	tdabe	sdibu
AIPHT	aipht	aihpt	aingt	oungs	FONCH	fonch	focnh	fokph	zikpr
CRUME	crume	cmure	cbule	nboli	FOTCH*	fotch	focth	forvh	birvs
GARLD	garld	galrd	gambd	fimbn	BORFS	borfs	bofrs	bokms	nakmn
SHRIE	shrie	srhie	slnie	glnao	GORST	gorst	gosrt	gonft	danfh
OFTIR*	oftir	otfir	onbir	anbem	VILEBY	vileby	vibely	visedy	nusadt
IMTERS	imters	itmers	ivpers	avpows	LANTED	lanted	latned	lafred	bofriz
SHIMTY*	shimty	shitmy	shifry	blafrn	HUCKER	hucker	hukcer	hubser	nibsow
THELSE	thelse	thesle	thepde	fripdo	GOCHED	goched	gohced	gojred	sijral
NISHES	nishes	nihses	nipres	buprot	DOGHTS	doghts	dohgts	dovpts	javpnz
ZANGED	zanged	zagned	zaphed	kophim	BLYANG	blyang	bylang	btpang	rtpiwk
BOMVER	bomver	bovmer	boxper	daxpid	BIRNET	birnet	binret	bifket	vafkow
WIBORD	wibord	wirobd	wipogd	mapugn	BASLED	basled	balsed	bafned	tofnir
NISHED	nished	nihsed	nirzed	farzib	OBIFED	obifed	ofibed	osihed	asuhan
BEMING	beming	benimg	bejisg	najosb	FOSNED	fosned	fonsed	fokred	bakrip
MISHOR*	mishor	mihsor	miplor	kapluw	NUMLED	numled	nulmed	nugped	bigpof
PHUNGS	phungs	phugns	phubrs	clibrt	NEOSTE	neoste	neotse	neorhe	yairhu
HIDTY	hidty	hitdy	hifby	pofbs	CHELE	chele	clehe	cmebe	dmubi
WHABE	whabe	wbahe	wlane	tlino	MOCKY*	mocky	mokcy	motry	watrd
OBFRY	obfry	obrfy	obndy	alndm	SHROW	shrow	srhow	stpow	gtpam
OARSH	oarsh	oasrh	oagdh	eigdn	NARFY	narfy	nafry	nacsy	mocsb
IMTOL	imtol	itmol	ibnol	abned	EDEBY	edeby	ebedy	enewy	onowp
BIPHT	bipht	bihpt	binkt	conkw	ASHOR	ashor	ahsor	atbor	itbaf
ANRED	anred	arned	asyed	isyof	OABLES	oables	oalbes	oacwes	iucwur
BYPONG	bypong	bpyong	bwtong	jwtash	CHONTY	chonty	chotny	chovky	slavkm
ZUMORY	zumory	zuromy	zuvopy	bavipt	SHORCH	shorch	shocrh	shoklh	plaklt
WUCKER	wucker	wukcer	wufper	mifpan	OBCERT	obcert	ocbert	ondert	andimp
GONRAY	gonray	gornay	gophay	laphit	GOCSON	gocson	goscon	golron	halrab
HORTON	horton	hotron	hoklon	jaklaf	OBISAL	obisal	osibal	ozigal	ezugem
ROUSHT	rousht	rouhst	roudmt	baidmn	PINTRE	pintre	pitnre	pisbre	fusbla
BEKROT	bekrot	berkot	bescot	jascip	BLYINS*	blyins	bylins	brpins	frpewz
FUBGRY	fubgry	fugbry	fuwjry	nawjlt	GABILY	gabily	galiby	gahity	dohutp
BLAFES	blafes	bfales	bjares	zjirov	IMRAYS	imrays	irmays	icvays	ucvont
BEDOLE	bedole	belode	benofe	munafu	VANKED	vanked	vakned	vaphed	ziphom
SHROOB	shroob	srhoob	slnoob	flneeg	FIGGLE	figgle	figlge	figthe	wontha

Note. ID = identity prime; TL = transposed letter prime; 2SL = two-substituted-letter prime; ALD = all-letter-different prime.
* Items removed from analyses.

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