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Transposed-character effects during learning to read: When does letter and non-letter strings processing become different?

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A B S T R A C T

Efficient reading requires the association of different letter identities with their positions in the written word. This leads to the development of a specialized mechanism for encoding flexible location-invariant letter positions through learning to read. In this study, we investigated not only the emergence and development of this position coding mechanism but also whether this mechanism is a consequence of the orthographic code (i.e., letter specific) or inherent to generic visual object recognition. To do so, the same–different matching task was used with children from Grade 1 to Grade 5 (Experiment 1) and with adults (Experiment 2). In both experiments, reference and target stimuli were composed of four-character strings (consonants, digits, and geometrical forms) and could be identical or different by transposing or substituting two internal characters. Analyses of response times, error rates, and discriminability indices revealed a transposed-character effect regardless of the type of characters in Grades 1 and 2, whereas transposed-character effects were greater for letter strings than for familiar non-letter strings in Grade 3, lasting up to Grade 5 as well as in adults. These results provided evidence in favor of a flexible position coding mechanism that is specific to letter strings,

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which emerges with reading experience as a consequence of parallel processing of letters within words.

Introduction

Efficient reading requires acquiring knowledge about letter identities and about their positions in the written word. Knowledge about letter identities allows novice readers to use a serial letter-by-letter reading strategy (i.e., phonological decoding), which ensures the connection of specific units that constitute an orthographic stimulus (i.e., written word) to their phonological representations. Serial letter processing provides the basis for constructing detailed orthographic representations that entail information about specific letter combinations and their positions within words (Grainger et al., 2016). This orthographic knowledge sets the ground for both accurate and fast word recognition as a consequence of parallel letter processing (Ehri, 2005, 2014; Grainger et al., 2012; Ziegler et al., 2014). This shift from a letter-by-letter strategy to faster and automatic access to whole words is a key aspect of becoming a skilled reader. In other words, reading experience implies a shift from serial, slow, and precise letter position encoding to parallel, fast letter position encoding, and this shift defines the optimal development of the child's reading system (Grainger & van Heuven, 2004; Grainger & Ziegler, 2011). In the current study, we assessed this shift by measuring transposition effects in children from Grade 1 to Grade 5 and in adults as well. Specifically, we addressed whether location-invariant letter position processing is a consequence of orthographic experience or is inherent to visual object recognition. In the following paragraphs, we first summarize the empirical evidence of the transposed-letter effects as a function of reading acquisition and the theoretical framework. Next, we introduce the experiment along with the hypotheses.

One phenomenon, the transposed-letter effect (henceforth TL effect), has particularly been used to investigate letter position encoding processes in children and adults. Studies exploring how words with transposed letters are processed support the notion that orthographic knowledge leads to a shift from location-specific processing of letters (typical of serial letter-by-letter reading), where letters are encoded in their specific positions, to location-invariant processing of letters (typical of parallel whole-word reading), where letters are encoded with certain position flexibility within words (Colombo et al., 2019; Ziegler et al., 2014). For instance, an impressive amount of evidence obtained from adults highlights that letter strings formed by transposing two letters of a real word are more often misidentified as their base word (e.g., "JUGDE" from "JUDGE") than letter strings formed by replacing two letters of the base word (e.g., "JUPTE" from "JUDGE") (Perea & Lupker, 2003, 2004; Schoonbaert & Grainger, 2004). These TL effects strongly point to a certain amount of flexibility in letter position coding (Davis, 2010; Gómez et al., 2008; Grainger & van Heuven, 2004; Norris et al., 2010; Whitney, 2001), which seems to increase from childhood to adulthood (Colombo et al., 2019). An important issue is when, during child development, this location-invariant processing mechanism emerges and how it develops as children gain reading experience.

To provide evidence of the emergence of TL effects during reading acquisition, Grainger et al. (2012) employed a lexical decision task in which children from Grade 1 to Grade 5 needed to identify whether the strings presented in isolation were words or not. The question was to trace when during development TL nonwords (e.g., "TALBE" for "TABLE") were misclassified as real words compared with control pseudowords (i.e., double letter substitution, e.g., "TARPE" for "TABLE"). The authors found that overall error rates were higher and decision times were longer in the TL pseudowords condition than in the replaced letter (henceforth RL) pseudowords condition and that this effect increased by grade (see also Colombo et al., 2017). Indeed, a linear increase in the size of TL effects has been found in children with a reading age under 9 years employing different paradigms, reflecting a shift from letter-specific to letter-invariant position coding mechanisms during the first years of reading acquisition.

For instance, using the sandwich version of the lexical decision masked priming task, Ziegler et al. (2014) replicated previous results in children from Grade 1 to Grade 5. In this paradigm, the target word is briefly presented (i.e., 27 ms, e.g., TABLE) before the prime stimulus that is displayed on the screen for 70 ms (e.g., talbe). The prime is then replaced with the target stimulus (e.g., TABLE), and participants are asked to perform a lexical decision task on the target stimulus. In Ziegler et al.'s (2014) investigation, target words were preceded by either a TL pseudoword prime (e.g., talbe) or an RL pseudoword prime (e.g., tarfe). The authors reported that TL priming effects (i.e., difference between the TL and RL prime conditions) increased monotonically with grade level and reading age in children from Grade 1 to Grade 5 (see also Lété & Fayol, 2013, with children in Grade 3 to Grade 5). More recently, Colombo et al. (2019) used the same paradigm to investigate whether the TL priming effect could be modulated by its position within the letter strings (i.e., transposed or replaced letters were either at the beginning or at the end of the prime), testing children in Grades 2, 3, and 5 as well as adults. Results revealed significant TL priming effects only for children in Grade 5 and adults regardless of the position of transposed or replaced letters within the prime. Furthermore, regression analyses performed on the *z*-transformed reaction times, confirmed that the size of the TL effect increased linearly during reading acquisition, although this increase was less evident between from Grade 2 to Grade 3.

These results fit well with the theoretical framework of orthographic development proposed by Grainger and Ziegler (2011). This framework assumes that at the beginning of reading acquisition, the serial letter-by-letter reading strategy allows matching between two types of information already known by the children: knowledge of the alphabet and phonological representations of spoken words. Each successful identification of a word strengthens the word-specific sublexical connections between its constituent letter sequence and the corresponding phonological sequence in lexical memory (Share, 1995). Consequently, a parallel letter processing mechanism develops that enables automatic activation of the whole word's orthographic representation (Grainger et al., 2016). This mechanism allows letter position coding based on the presence of letter combinations within the word with no information about precise position. Letter combinations are processed via open bigrams (Grainger & van Heuven, 2004; Grainger & Whitney, 2004), which are the most informative to determine a word's identity irrespective of letter contiguity. This code provides a rapid but not foolproof bottom-up activation of whole-word representations, leading to the development of a flexible location-invariant letter position mechanism that allows automatic identification of words. Such orthographic processing is a key aspect of becoming a skilled reader through efficient access to semantics via parallel letter processing. The key issue in this framework is that the development of letter encoding mechanisms is understood as a result of the child's experience with written words.

An important caveat of the studies mentioned above is that although they have provided important information about how the letter position encoding mechanisms change, they do not allow disentangling whether this occurs as a result of experience with written words. Some authors suggest that the mechanism used to code for letter position might not be the same as could be used to code positional information of strings made by any kind of visual characters (e.g., digits, symbols, geometrical forms; see Duñabeitia et al., 2012; Massol et al., 2013, Massol & Grainger, 2022, 2024). Indeed, if the letter-invariant position mechanism is a result of experience with written words, the transposition effects should emerge for letter strings but not for other types of visual characters.

The same–different matching task has been mainly employed to test this hypothesis given that it taps into perceptual automatic processes as well as into higher-level order-encoding processes (see Massol & Grainger, 2022, for empirical evidence with adults). In this paradigm, a first stimulus is displayed (*reference,* i.e., 300 ms) and is immediately followed by a second stimulus (*target,* i.e., 300 ms). Participants need to judge, as rapidly and accurately as possible, whether the stimuli are the same or not. Studies employing this paradigm in adults have revealed that transposition effects are larger for consonant letter strings (e.g., DKLNFT–DLKNFT vs. DKLNFT–DSGNFT) than for non-alphabetic strings (e.g., 623145–632145 vs. 623145–698145) (Duñabeitia et al., 2012; Massol et al., 2013; Massol & Grainger, 2022, 2024).

Duñabeitia et al. (2015) employed the same–different matching task to examine the letter transposition effect (i.e., greater difficulty in detecting a difference with transpositions compared with double substitutions) in children from kindergarten to Grade 1. In the critical different conditions, a four-letter target string matched the reference except for two internal transposed letters (i.e., different TL condition, e.g., rszk–rzsk) or for two internal replaced letters (i.e., different RL condition, e.g., rzsk–rchk). The authors found robust TL costs in children only when they had acquired basic literacy skills, suggesting that the TL effect emerges as a consequence of literacy. Tóth and Csépe (2017) tested this issue further in Hungarian children from Grade 2 to Grade 4 by comparing the TL effect with Hungarian letter strings and with Armenian letter strings (which were completely unknown to children). Whereas strong TL effects were found for Hungarian letter strings, no effect was reported for Armenian letter strings. In addition, the TL effect for Hungarian letter strings increased across grades, supporting the view that the transposition effect is reliant on experience with print.

Although these results suggest that location invariant processes are specific to letter strings as a result of reading experience, to date no study has examined the development of position coding for letters in letter strings and for familiar characters in character strings (i.e., digit strings and strings of geometrical forms) during the first years of reading acquisition. The theoretical framework of Massol and Grainger (2022; see also Massol & Grainger, 2024) makes specific predictions about this issue. To address the progression from location-specific processing to location-invariant processing, two levels of visual processing are distinguished. The generic-level computations would operate on any type of character. Critically, at the letter-specific processing level, the letter order-encoding mechanisms is fed by the experience with many letter sequences. This disproportionate experience with letter sequences (in contrast to other characters) allows relative and flexible position coding for letters compared with other types of visual characters. Therefore, TL effects are hypothesized to be driven by (a) perceptual noise at a location-specific level due to visual feature detectors that affect positional coding of any kind of character string at any point during development and (b) flexibility of letter position coding as a result of experience with printed words. According to this rationale, certain transposed-character effects should be expected for any kind of visual objects at any age, whereas only TL effects should increase with reading experience.

This study aimed to investigate these hypotheses by testing whether the emergence and development of the location-invariant letter position mechanism is a consequence of experience with the orthographic code or inherent to generic visual object recognition. This investigation went beyond previous studies in several important ways. First, it evaluated a larger range of children from Grade 1 to Grade 5 (Experiment 1) and a group of adults (to replicate previous findings with the same set of materials used in Experiment 1) (Experiment 2). Second, it compared the developmental trajectory of position coding for different kinds of characters employing the same paradigm, namely the same–different matching task. To that aim, we presented strings of letters, digits, and geometrical forms that were all four characters long. In the critical conditions requiring a "different" response, the target matched the reference except for two internal transposed characters (i.e., different transposed-character condition, e.g., PVGK–PGVK) or except for two internal replaced characters (i.e., different replaced character condition, e.g., PJMK–PGVK). Based on the literature and on the theoretical framework proposed by Massol and Grainger (2022), we expected a main transposition effect regardless of the type of characters in beginning readers (i.e., children in Grades 1 and 2), but an increasing magnitude of transposed-character effect for letter strings compared with non-letter strings as children gain reading experience.

Experiment 1: Children

Method

Participants

A total of 216 children from Grade 1 to Grade 5 were recruited from three different public elementary schools at the end of the school year. Given that reading instruction in France follows a tight national curriculum, we presumed school effects as well as teacher effects on transposition costs to be negligible. Children had normal or corrected-to-normal vision, were monolingual native speakers of French, and had no history of a specific learning disorder. Children who performed below the normal range on a standardized reading test (L'Alouette; Lefavrais, 1967) (n = 10) or who were unable to complete the task (n = 25) (see Results) were excluded from analyses. Characteristics of the final sample of 181 children are presented in Table 1.

Ethics approval was obtained from the ethics committee of the Université de Lyon. A parent or legal representative of each child provided informed consent prior to inclusion of the child in the experiments.

Materials

A total of 240 reference–target pairs were used as stimuli. Each of the pairs was composed of two four-character strings of uppercase consonants, digits, or familiar geometrical forms. These three categories consisted of 80 letter strings, 80 digit strings, and 80 strings of geometrical forms. For the digit strings, the numbers 1, 2, 3, 4, 5, 6, 7, 8, and 9 were used. For the letter strings, the uppercase versions of the consonants B, D, F, G, K, L, N, S, and T were used. The forms used to create the geometrical form strings all were familiar forms: noon, triangle, square, star, right arrow, down arrow, heart, circle, and cross. Digit strings and strings of geometrical forms were created by recoding the letters of each letter string according to an arbitrary recoding scheme (e.g., B → 2 → moon).

In each category, half of the items (120 trials) required a "same" response (e.g., DKLN–DKLN). The other half (120 trials) required a "different" response. For the "different" trials, targets could be preceded either by references created by transposing two characters (20 pairs for each type of character string, e.g., P<u>VG</u>K–P<u>GV</u>K) or by references created by replacing two characters (20 pairs for each type of character string, e.g., P<u>JM</u>K–P<u>GV</u>K). Critically, transpositions or substitutions never involved the outer characters. In each list, each reference was presented twice, once requiring a "same" response and once requiring a "different" response, whereas each target occurred only once. Following a counterbalanced design, the reference–target pairs were separated into two subsets to create two lists of experimental stimuli that were presented to different participants. Character (letters, digits, or geometrical forms) was crossed with type of change (transposition or substitution) and with grade (Grade 1, 2, 3, 4, or 5) in a 3 × 2 × 5 factorial design.

Procedure

The presentation of the stimuli and recording of the responses were carried out using DMDX software (Forster & Forster, 2003). Participants were informed that two strings of characters were going to be subsequently displayed. All stimuli were presented in white Courier New font on a black background. Each trial began with the centered presentation of a fixation stimulus (+) displayed for 500 ms. Immediately after, the reference was presented for 1000 ms horizontally centered and positioned one line above the exact center of the screen. The reference was immediately replaced by the target stimulus that was horizontally centered and positioned one line below the center of the screen. The target stimulus remained on the screen until a response was given or after 3000 ms had elapsed. Each trial ended with a blank screen displayed for 500 ms. The manipulation of the location of references and targets on the vertical axis was carried out in order to avoid physical overlap between the

Table 1
Characteristics of the sample

	Final sample of 181 children			
Grade	n	Gender (boys/girls)	Chronological age in months	Reading age at L'Alouette in months
1	29	15/14	79.54 (3.78)	79.90 (4.35)
2	50	27/23	93.96 (5.56)	95.38 (13.71)
3	38	20/18	105.76 (3.99)	112.97 (20.17)
4	31	15/16	116.16 (3.52)	115.84 (10.31)
5	33	16/17	125.94 (4.65)	127.39 (16.65)

Note. Standard deviations are in parentheses.

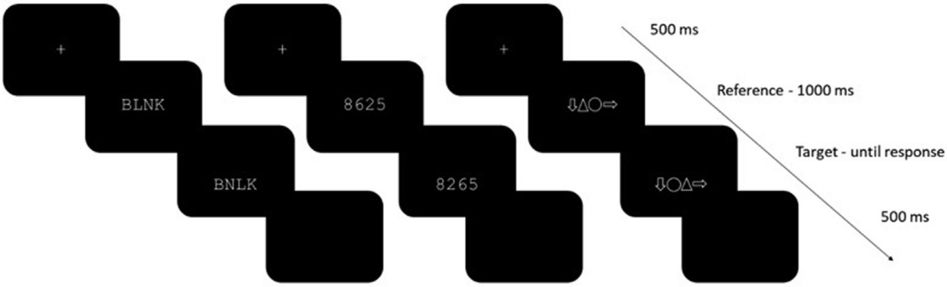

Fig. 1. Schematic representations of trials using the same–different matching paradigm.

two strings (see Fig. 1 for a schematic representation of a trial). Participants were instructed to decide as rapidly and accurately as possible whether or not the two strings were exactly identical. They responded "same" by pressing the "L" button on the keyboard and responded "different" by pressing the "S" button. The experiment was divided into three separate blocks that included only items belonging to the same stimulus category. A short practice session was administered before the main experiment to familiarize participants with the procedure and the task. Children were tested in small groups of 3 to 5 by two or three experimenters in the same room in a single 25-min session.

Results

Statistical analyses were performed only over the "different" trials given that there was no experimental manipulation within the set of "same" trials. Incorrect responses (22.99% of the data) and response times (RTs) under 300 ms (1.48% of the data) were excluded from RT analysis. Then the RTs that were 3 standard deviations beyond the mean of the participant were excluded as outliers (1.08% of the data). Finally, for each participant, each RT for a correct response was transformed into a *z*-score value by subtracting the RT value from the participant's grand mean obtained across the three priming conditions and dividing the resulting value by the standard deviation of the grand mean. Mean RT *z*-scores were then computed for each participant in each of the experimental conditions. Indeed, as highlighted by Faust et al. (1999), there is often a linear relation between the RTs observed for different groups, and this can lead to the finding of spurious interactions over additive interactions in which the slower group produces a larger treatment effect. These authors then recommended performing *z*-score transformations on RTs in order to remove group differences in processing speed. They argued that comparing the results of analyses of raw versus transformed latencies should help researchers to better identify and interpret any interaction that implies the factor group (i.e., grade factor in the current experiment) (see Lété & Fayol, 2013, for a similar procedure).

We used linear mixed-effects models (LMEs) to analyze *z*-score values (RT *z*-scores) and used generalized (logistic) linear mixed-effects models (GLMEs) to analyze the error rates, with items and participants as crossed random effects (including by-item and by-participant random intercepts) (Baayen et al., 2008) and with random slopes (Barr et al., 2013). Models included grade (Grade 1, 2, 3, 4, or 5), character (letter, digit, or symbol), and type of change (transposition or substitution) as fixed factors. The models were fitted with the *lmer* function (for LMEs) and with the *glmer* function (for GLMEs) from the "lme4" package (Bates et al., 2014) in the R statistical computing environment (Version 4.2.2) (R Core Team, 2022).

In addition, participants' discriminability indices (d') were analyzed using signal detection theory (Macmillan & Creelman, 2004). Compared with simple error rate analyses, discriminability corrects for response biases by combining hits (correct "different" responses) with false alarms (incorrect "different" responses, i.e., responding "different" when the two stimuli were the same). Discriminability was calculated for each participant in the different experimental conditions. These analyses are available in the online supplementary material.

A total of 25 participants were excluded prior to analysis (2 participants had an overall d' value equal to 0, 3 participants had a valid trial rate under 55%, 17 participants had an accuracy rate under 55%, and 3 participants had an error rate at 100% in one experimental condition). The remaining sample was composed of 181 participants (see Table 1 for statistics about gender, chronological age, and reading age).

The mean RTs, error rates, and discriminability indices in each condition are presented in Table 2.

RT z-scores

The maximal random effects structure that converged was one including by-participant and by-item random intercepts. The following analyses were conducted taking the letter string condition as reference for the character factor, taking the substitution condition as reference for the type of change factor, and taking Grade 1 as reference for the grade factor. To simplify the description of the model outputs, here we summarize only the main effects and the three-way interaction of Grade × Character × Type of Change. See Appendix A in the supplementary material for the complete model outputs. Transposition costs on RT *z*-scores for each type of character as a function of grade are presented in Fig. 2.

The main analysis revealed that the effect of grade was not significant, $\chi^2(4) = 0.29$, $p > .10$. There was a main effect of character, $\chi^2(2) = 45.97$, $p < .001$. Follow-up analyses revealed that there was a significant difference between letter strings and digit strings (0.10 vs. -0.03 *SD*, respectively), $\chi^2(1) = 37.06$, $p_{\text{Holm}} < .001$, a significant difference between letter strings and strings of geometrical forms (0.10 vs. 0.03 *SD*, respectively), $\chi^2(1) = 13.23$, $p_{\text{Holm}} < .001$, and a significant difference between digit strings and strings of geometrical forms (-0.03 vs. 0.03 *SD*, respectively), $\chi^2(1) = 5.85$, $p_{\text{Holm}} = .001$. There was also a main effect of type of change (0.19 vs. -0.12 *SD*, respectively), $\chi^2(1) = 414.32$, $p < .001$. The two-way interactions all were significant (see Appendix A in the supplementary material for further details). Importantly, the three-way interaction of Grade × Character × Type of Change was significant, $\chi^2(8) = 26.05$, $p = .001$. Follow-up analyses were performed within each grade to reveal whether the transposition effect was modulated by the type of character. The Character × Type of Change interaction was not significant in Grade 1, $\chi^2(2) = 1.75$, $p > .10$, or in Grade 2, $\chi^2(2) = 3.17$, $p > .10$, whereas it was significant starting in Grade 3 [Grade 3: $\chi^2(2) = 41.62$, $p < .001$; Grade 4: $\chi^2(2) = 6.17$, $p = .004$; Grade 5: $\chi^2(2) = 112.20$, $p < .001$]. Altogether, these results showed that the

Table 2
Mean correct response times (in ms) and mean error rates as a function of type of character and type of change pair (transposition or substitution) in Experiment 1

	Type of change	Letters		Digits		Geometrical forms	
		RT	Error rate	RT	Error rate	RT	Error rate
Grade 1	Transposition	1420 (326)	45.07 (22.11)	1544 (358)	43.93 (22.22)	1537 (396)	44.92 (20.38)
	Substitution	1383 (220)	30.50 (20.19)	1407 (236)	30.35 (20.48)	1490 (261)	28.28 (20.13)
	Transposition cost	41	14.57	137	13.58	47	16.64
Grade 2	Transposition	1437 (309)	48.41 (20.84)	1419 (322)	35.32 (17.48)	1437 (262)	43.34 (23.72)
	Substitution	1326 (270)	25.56 (22.17)	1308 (265)	21.54 (17.26)	1389 (229)	25.95 (18.86)
	Transposition cost	112	22.84	110	13.79	48	17.39
Grade 3	Transposition	1450 (282)	37.21 (21.47)	1326 (241)	19.13 (13.42)	1234 (198)	31.23 (20.96)
	Substitution	1182 (175)	9.35 (13.85)	1182 (216)	9.70 (10.79)	1209 (199)	15.20 (15.16)
	Transposition cost	269	27.86	144	9.43	25	16.03
Grade 4	Transposition	1322 (258)	36.09 (19.58)	1201 (253)	24.04 (14.65)	1256 (281)	31.19 (17.70)
	Substitution	1159 (230)	13.21 (10.42)	1118 (241)	11.34 (13.95)	1169 (282)	18.12 (14.85)
	Transposition cost	163	22.87	83	12.70	87	13.06
Grade 5	Transposition	1308 (241)	30.92 (18.84)	1160 (201)	16.09 (11.65)	1173 (172)	26.43 (17.75)
	Substitution	1130 (171)	11.08 (13.35)	1105 (314)	10.85 (18.54)	1103 (198)	14.30 (12.53)
	Transposition cost	187	19.84	55	5.24	70	12.14

Note. Standard deviations are in parentheses. RT, response time.

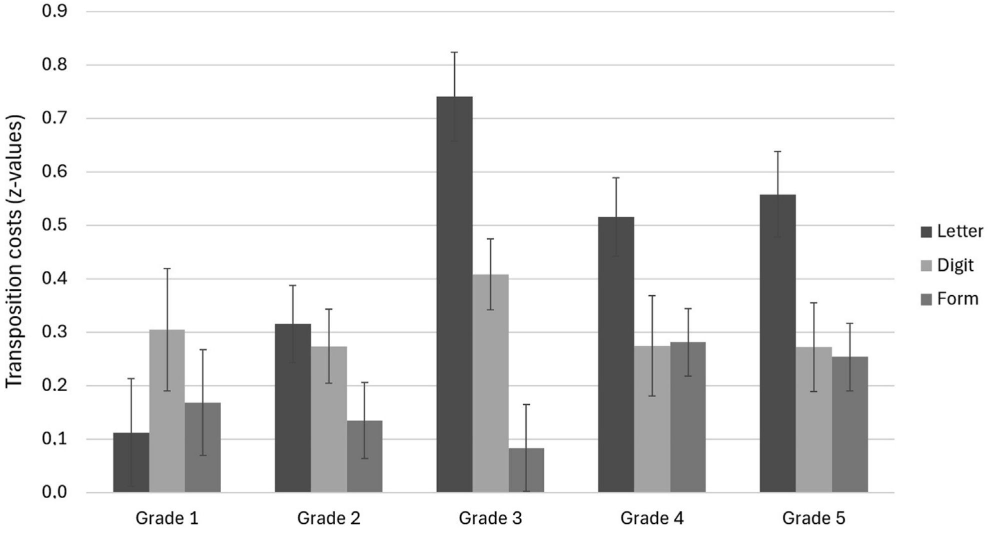

Fig. 2. Transposition costs (in *z*-values) for response times in Experiment 1. Transposition costs for each type of character for the five groups of children (Grades 1–5) are shown. Error bars represent standard errors. Transposition cost equals substitution condition minus transposition condition.

Table 3
Transposed-character effects on RT *z*-scores and error rates for all types of characters in each grade (Experiment 1)

		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Letters	RT *z*-score	$\chi^2(1) = 2.93$, $p = .086$	$\chi^2(1) = 34.19$, $p < .001$	$\chi^2(1) = 129.36$, $p < .001$	$\chi^2(1) = 52.48$, $p < .001$	$\chi^2(1) = 85.24$, $p < .001$
	Error rate	$\chi^2(1) = 27.68$, $p < .001$	$\chi^2(1) = 118.66$, $p < .001$	$\chi^2(1) = 43.29$, $p < .001$	$\chi^2(1) = 83.61$, $p < .001$	$\chi^2(1) = 77.27$, $p < .001$
Digits	RT *z*-score	$\chi^2(1) = 12.70$, $p = .001$	$\chi^2(1) = 30.44$, $p < .001$	$\chi^2(1) = 57.80$, $p < .001$	$\chi^2(1) = 22.15$, $p < .001$	$\chi^2(1) = 26.64$, $p < .001$
	Error rate	$\chi^2(1) = 22.90$, $p < .001$	$\chi^2(1) = 51.60$, $p < .001$	$\chi^2(1) = 204.07$, $p < .001$	$\chi^2(1) = 35.44$, $p < .001$	$\chi^2(1) = 11.03$, $p < .001$
Forms	RT *z*-score	$\chi^2(1) = 5.03$, $p = .004$	$\chi^2(1) = 12.60$, $p < .001$	$\chi^2(1) = 5.67$, $p < .001$	$\chi^2(1) = 16.71$, $p < .001$	$\chi^2(1) = 14.00$, $p < .001$
	Error rate	$\chi^2(1) = 35.95$, $p < .001$	$\chi^2(1) = 67.07$, $p < .001$	$\chi^2(1) = 28.18$, $p < .001$	$\chi^2(1) = 28.08$, $p < .001$	$\chi^2(1) = 32.41$, $p < .001$

Note. The *p*-values were corrected for multiple comparisons using Holm correction. RT, response time.

transposed-character effect was significantly larger for letter strings than for both strings of digits and strings of geometrical forms starting in Grade 3 (see Table 3).

Error rates

The maximal random effects structure that converged was one including by-participant and by-item random intercepts. The following analyses were conducted taking the letter string condition as reference for the character factor, taking the substitution condition as reference for the type of change factor, and taking Grade 1 as reference for the grade factor. To simplify the description of the model outputs, here we summarize only the main effects and the three-way interaction of Grade × Character × Type of Change. See Appendix B in the supplementary material for the complete model outputs. Transposition costs on error rates for each type of character as a function of grade are presented in Fig. 3.

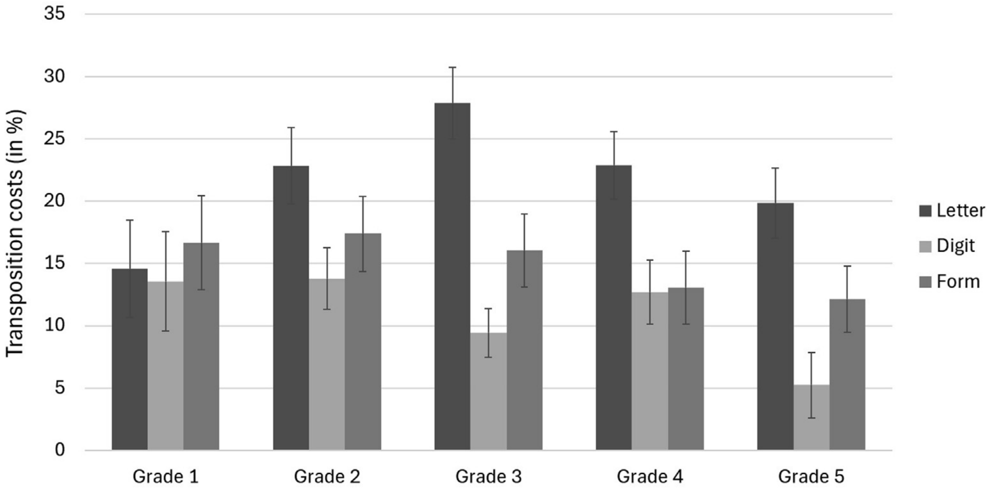

Fig. 3. Transposition costs for error rates in Experiment 1. Transposition costs for each type of character for the five groups of children (Grades 1–5) are shown. Error bars represent standard errors. Transposition cost equals substitution condition minus transposition condition.

The main analysis revealed a main effect of grade, $\chi^2(4) = 50.17$, $p < .001$, as well as a main effect of character, $\chi^2(2) = 57.70$, $p < .001$. Follow-up analyses revealed higher error rates for letter strings than for digit strings (28.74 vs. 22.23%, respectively), $\chi^2(1) = 34.32$, $p_{\text{Holm}} = .001$, and higher error rates for strings of geometrical forms than for digit strings (27.90 vs. 22.23%, respectively), $\chi^2(1) = 40.31$, $p_{\text{Holm}} < .001$, whereas the comparison between letter strings and strings of geometrical forms was not significant (28.74 vs. 27.90%, respectively), $\chi^2(1) < 1$, $p_{\text{Holm}} > .10$. There was also a main effect of type of change, with higher error rates in the transposition condition than in the substitution condition (34.22 vs. 18.36%, respectively), $\chi^2(1) = 737.45$, $p < .001$. The two-way interactions all were significant (see Appendix B in the supplementary material for further details). Importantly, the three-way interaction of Grade × Character × Type of Change was significant, $\chi^2(8) = 20.91$, $p = .003$. Follow-up analyses were performed within each grade to reveal whether the transposition effect was modulated by the type of character. The Character × Type of Change interaction was not significant in Grade 1, $\chi^2(2) = 0.87$, $p > .10$, whereas it was significant starting in Grade 2 [Grade 2: $\chi^2(2) = 6.83$, $p = .003$; Grade 3: $\chi^2(2) = 28.18$, $p < .001$; Grade 4: $\chi^2(2) = 9.50$, $p < .001$; Grade 5: $\chi^2(2) = 12.97$, $p = .001$]. Altogether, these results showed that the transposed-character effect was larger for letter strings than for both strings of digits and strings of geometrical forms starting in Grade 2 (see Table 3).

Discussion

The aim of this experiment was to investigate the emergence and development of the letter-specific coding mechanism during reading acquisition and to explore whether the position coding mechanism operates both for letters and for any kind of visual objects. Overall, the results highlighted that the size of the transposed-character effect started to differ for letters, digits, and geometrical forms in Grade 3 in the RT data. Regarding error rates, the size of the transposition cost started to differ in Grade 2. Therefore, the size of the transposition effect was not modulated by the type of character strings in Grades 1 and 2. That is, participants found it harder (i.e., longer RTs and more errors) to decide that two strings differed by a character transposition than to decide that two strings differed by a character substitution regardless of the type of characters. Nonetheless, important changes in this pattern were observed in older children. Starting in Grade 3 and lasting up to Grade 5, the sizes of transposition effects for letters differed significantly from those of transposition effects obtained with both digits and geometrical forms. Transposition effects were larger for letters as compared with both digits and geometrical forms, which did not differ from each other. Altogether, we interpret these findings as strong evidence in favor of a letter-specific position coding mechanism, which is more flexible as a consequence of the development of orthographic code. The transposition effect found for all types of character strings in beginning readers (i.e., Grades 1 and 2) as well as in intermediate readers (i.e., Grades 3–5) can be interpreted as the result of perceptual noise for a visual feature detecting mechanism that operates at a location-specific level for any kind of character (Massol & Grainger, 2022). Starting in Grade 3, the greater transposition effects seen with letter strings can be interpreted as reflecting the impact of a letter-specific, location-invariant order-encoding mechanism. According to the theoretical framework proposed by Massol and Grainger (2022), location-specific representations of complex features provide information that a given character is present in the stimulus array at a particular location relative to eye fixation. Positional noise would operate at a location-specific level for complex feature detector processing and therefore would apply to the processing of strings of different kinds of stimuli (see Fig. 4). This level of processing therefore is not restricted to the reading system, which explains why reading acquisition did not influence such perceptual processes. For children in Grades 1 and 2, results highlighted a "same" impact on same–different judgments to the three types of stimuli, suggesting that transposed-character effects are driven by positional noise due to a noisy encoding of character location that operated at the level of feature detectors. However, because reading experience is more extensive, an independent letter processing mechanism develops (Grainger & Ziegler, 2011), which allows the coding of letter position within the letter string via open bigram representations (Grainger & van Heuven, 2004). The development of such processing optimizes the access to semantics from orthography and involves letter-specific, location-invariant order encoding that accounts for greater transposition costs for letters than for any other types of familiar non-alphabetic character strings (i.e., digits and geometrical forms), as found in intermediate readers (i.e., Grades 3–5).

To test this hypothesis further, we ran the same experiment in adults. Experiment 2 aimed at replicating with adults previous findings on transposition effects obtained with letters as compared with non-alphabetic character strings (Duñabeitia et al., 2012; Massol et al., 2013; Massol & Grainger, 2022, 2024), using the exact same stimuli as those used with children in Experiment 1. If greater transposition costs for letters than for both digits and geometrical forms are due to extensive experience with written words, adults should show the same pattern as found in children in Grades 3 to 5.

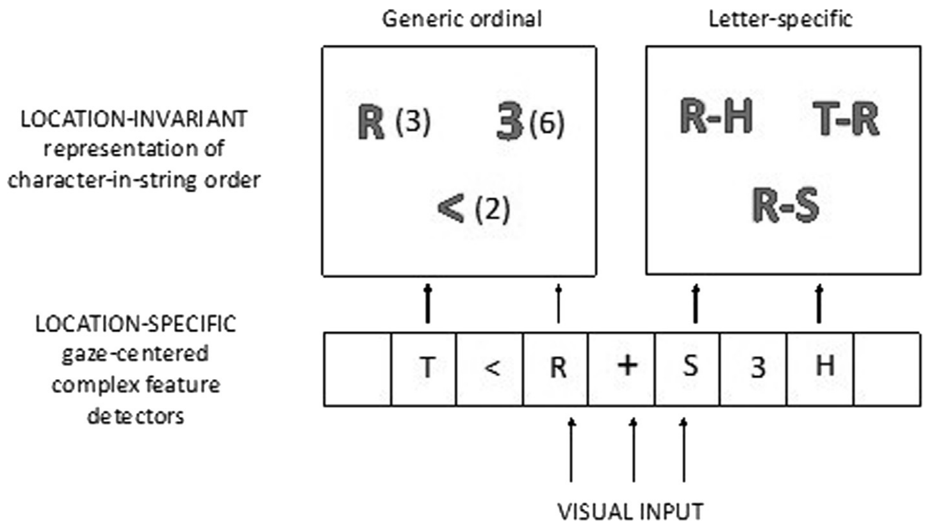

Fig. 4. Theoretical framework for the processing of identity and order information for same–different matching with strings of letters, digits, or symbols proposed by Massol and Grainger (2022).

Experiment 2: Adults

Method

Participants

The initial sample consisted of 50 participants (18 male; mean age = 20 years, *SD* = 4.09). All participants were monolingual native speakers of French. All participants performed a standardized reading test (L'Alouette; Lefavrais, 1967) that provides their reading level measured as reading age to ensure that they did not have any reading impairments. Participants who reported language impairments and/or a formal diagnosis of dyslexia were excluded from this study (i.e., non-inclusion criteria). All participants gave their informed consent prior to their inclusion in the study.

Stimuli

Stimuli used in this experiment were the same as those used in Experiment 1.

Procedure

The procedure of Experiment 2 mimicked the procedure used in the previous experiment. The procedure for each trial was the same as in Experiment 1 (see Fig. 1) except that durations of the stimuli on the screen were adjusted according to previous investigations using the same–different matching task with adults (Duñabeitia et al., 2012; Massol et al., 2013; Massol & Grainger, 2022, 2024). That is, after the fixation cross, the reference was presented horizontally centered and positioned one line above the exact center of the screen for a duration of 300 ms. The reference was immediately replaced by the target stimulus that was horizontally centered and positioned one line below the center of the screen. The target stimulus remained on the screen for 300 ms. Each trial ended with the participant's response, followed by a blank screen displayed for 500 ms.

Results

Statistical analyses were performed only over the "different" trials given that there was no experimental manipulation of type of change within the set of "same" trials. The dataset from 1 participant was excluded based on an overall error rate above 40%.

As in Experiment 1, participants' discriminability indices were analyzed using signal detection theory (Macmillan & Creelman, 2004). Discriminability was calculated for each participant in the different experimental conditions. These analyses are available in the supplementary material.

We used LMEs to analyze RTs and used GLMEs to analyze error rates, with items and participants as crossed random effects (including by-item and by-participant random intercepts) (Baayen et al., 2008) and with random slopes (Barr et al., 2013). Models included character (letter, digit, or symbol) and type of change (transposition or substitution) as fixed factors. The models were fitted with the *lmer* function (for LMEs) and the *glmer* function (for GLMEs) from the "lme4" package (Bates et al., 2014) in the R statistical computing environment (Version 4.2.2) (R Core Team, 2022). We report regression coefficients (b), standard errors (SE), and t-values (for LMEs) or z-values (for GLMEs). Fixed effects were deemed significant if $|t|$ or $|z| > 1.96$. RTs were inverse-transformed (-1000/RT) prior to analysis. The mean RTs and error rates in each condition are presented in Table 4.

Table 4
Mean correct response times (in ms) and mean error rates for different trial pairs (transposition or substitution) in Experiment 2

Type of change	Letters		Digits		Geometrical forms	
	RT	Error rate	RT	Error rate	RT	Error rate
Transposition	746 (151)	30.67 (23.94)	704 (140)	16.98 (19.68)	746 (166)	30.84 (24.38)
Substitution	661 (110)	6.03 (15.71)	652 (114)	3.72 (5.97)	699 (124)	13.64 (13.14)
Transposition cost	70	24.64	51	13.26	46	17.20

Note. Standard deviations are in parentheses. RT, response time.

RTs were recorded from target onset up to participant's response. After excluding trials associated with an incorrect response (11.33%), RT values under 300 ms were also excluded (0.88%). Then the RTs that were 3 standard deviations beyond the mean of the participant were excluded as outliers (1.48% of the data). The final dataset was composed of 4772 observations.

Response times

The maximal random effects structure that converged was one including by-participant and by-item random intercepts as well as by-participant and by-item random slopes for type of change. The following analyses were conducted taking the letter string condition as reference for the character factor and taking the substitution condition as reference for the type of change factor.

RTs were longer for letter strings than for digit strings (704 vs. 678 ms, respectively), b = -0.03, SE = 0.01, t = -2.54, whereas RTs were shorter for letter strings than for strings of geometrical forms (704 vs. 722 ms, respectively), b = 0.05, SE = 0.01, t = 3.87. There was also a significant effect of type of change, with shorter RTs in the substitution condition than in the transposition condition (671 vs. 732 ms, respectively), b = 0.16, SE = 0.01, t = 9.38. The interaction between character (letters or digits) and type of change was significant, b = -0.16, SE = 0.02, t = -3.00, as was that between character (letters or geometrical forms) and type of change, b = -0.08, SE = 0.02, t = -3.98. Transposition effects were greater for letters compared with both digits and geometrical forms, although the effects were significant for all types of characters [letters: $\chi^2(1) = 88.05$, $p_{\mathrm{Holm}} < .001$; digits: $\chi^2(1) = 37.68$, $p_{\mathrm{Holm}} < .001$; geometrical forms: $\chi^2(1) = 19.48$, $p_{\mathrm{Holm}} < .001$].

Error rates

The maximal random effects structure that converged was one including by-participant and by-item random intercepts as well as by-participant random slopes for type of change. The following analyses were conducted taking the letter string condition as reference for the character factor and taking the substitution condition as reference for the type of change factor.

Error rates were higher for letter strings than for digit strings (10.35 vs. 18.35%, respectively), b = -0.54, SE = 0.236, z = -2.29, whereas error rates were lower for letter strings than for strings of geometrical forms (18.35 vs. 22.24%, respectively), b = 1.03, SE = 0.19, z = 5.32. Higher error rates were observed in the transposed-character condition than in the substituted-character condition (26.16 vs. 7.80%, respectively), b = 2.33, SE = 0.21, z = 11.00). The interaction between character (letters or geometrical forms) and type of change was significant, b = -1.02, SE = 0.20, z = -4.91, whereas the interaction between character (letters or digits) and type of change was not significant, z = -1.56. Transposition effects were greater for letters compared with both digits and geometrical forms, although the effects were significant for all types of character [letters: $\chi^2(1) = 121.02$, $p_{\mathrm{Holm}} < .001$; digits: $\chi^2(1) = 62.96$, $p_{\mathrm{Holm}} < .001$; geometrical forms: $\chi^2(1) = 52.15$, $p_{\mathrm{Holm}} < .001$].

Discussion

Experiment 2 replicated previous findings obtained in adults where greater letter transposition effects were found with respect to letter substitution in the classical (unprimed) version of the same–different matching task (Massol et al., 2013; Massol & Grainger, 2022, 2024). Our results with adults supported the view that the transposition effect for letters is a consequence of reading experience, with this effect being greater for letters than for digits and geometrical forms (see also Duñabeitia et al., 2012; Massol et al., 2013, Massol & Grainger, 2022, 2024, for TL and character evidence with adults). Overall, the pattern of results found in children in Grade 3 was highly similar to the pattern found in adults. These results strongly suggest that the TL effect is mainly driven by (a) an object position uncertainty, and a perceptual noise at a location-specific level, that affects any kind of character strings and by (b) a flexibility of orthographic processing that involves location-invariant relative position coding for letter strings as a result of experience with written words (see General Discussion).

It should be mentioned that Garcia-Orza et al. (2010), using a masked priming version of the same–different matching task (transposition effect was measured in the "same" condition), highlighted similar priming effects of transposed characters with letter strings (words and nonwords), digits, and symbols with adults. Therefore, the mechanisms driven by the masked and unmasked versions of the same–different task seem to be different. One main interpretation is that the masked priming version of the same–different judgment task likely highlights early visual processing compared with the classical (unmasked) version of same–different matching, which is more optimal to tap into both early visual processing and higher-order-encoding processes. In other words, the masked version may enhance low-level perceptual effects (i.e., location-specific encoding) as opposed to higher-level effects (i.e., location-invariant order encoding) (see Duñabeitia et al., 2012, for a discussion about masked vs. unmasked versions of the same–different matching task).

General discussion

The current study employed a same–different matching task to test two different but complementary accounts about how letter encoding mechanisms change with reading experience. According to the theoretical approach proposed by Grainger and Ziegler (2011), the TL effect emerges with reading exposure via the development of parallel letter processing. Therefore, we expected greater TL effects once more extensive reading experience is attained. However, this framework is restricted to orthographic processing, and no prediction can be made about transposed-character effects for other kinds of visual objects. Recently, Massol and Grainger (2022) proposed an appealing account, based on empirical data obtained in the same–different matching task with adults. They hypothesized that the greater transposition cost obtained with letter strings compared with that obtained with digit and symbol strings is driven by two mechanisms: (a) one at the location-specific level, which is subject to a certain amount of positional noise, and (b) one at the location-invariant level, which is a letter-specific order-encoding mechanism that is flexible by nature. Based on these accounts, we traced the developmental trajectory of transposed-character effects for letter strings and for familiar non-letter character strings (i.e., digits and geometrical forms) in children from Grade 1 to Grade 5 (Experiment 1) and in adults (Experiment 2). We predicted that in beginning readers transposed-character effects would be obtained regardless of the type of characters. Nonetheless, once more extensive reading experience is attained, a greater transposed-character effect is expected for letters compared with digits and geometrical forms.

To test such predictions, in both experiments reference–target pairs were similar or different by transposing or substituting the two internal characters of the strings. Participants were asked to decide whether reference and target stimuli were identical or not. In Experiment 1, we found that children made more errors at detecting a transposition change than at detecting a substitution change—an effect referred to as a transposition cost—for all types of characters across all grades. More important, we also found a greater transposition cost for letters than for both digits and geometrical forms (which did not differ from each other) in children with more extensive reading experience—starting in Grade 3. Experiment 2 supported the findings obtained in Grades 3 to 5 in Experiment 1 and replicated previous findings with adults reporting greater character transposition cost for letter strings than for familiar non-letter character strings (Duñabeitia et al., 2012; Massol et al., 2013; Massol & Grainger, 2022, 2024).

Regarding the TL effect as an index of this transition for serial to parallel processing, several studies have found an increase of TL effects in children from Grade 1 to Grade 5 (Colombo et al., 2019; Ziegler et al., 2014). These studies provide evidence for the development of an automatic and rather efficient orthographic processing mechanism during the first years of reading acquisition that involves the emergence of a letter-specific position coding mechanism (see also Grainger et al., 2012; Lété & Fayol, 2013). Altogether, these previous results and those from the current study are in line with the accounts proposed by Grainger and Ziegler (2011). According to this framework, during reading acquisition there is a shift from a letter-by-letter strategy to faster and more efficient access to lexical–semantic representations, partly through the development of parallel letter processing. This parallel letter processing allows the establishment of sub-lexical orthographic processing (determining letters' identities and order in a word). Note that learning to read also involves adaptations in the low-level visual processing involved in identifying strings of letters (Grainger et al., 2016; Grainger & Hannagan, 2014; Tydgat & Grainger, 2009). This implies a change of letter status from being objects themselves to being parts of a written word, along with the establishment of location-specific letter detectors aligned along the horizontal meridian in order to optimize parallel letter processing (Grainger & Hannagan, 2014). Interestingly, while this transition takes place, there is also a shift from a precise letter order encoding used for phonological decoding to a more flexible letter order code. The development of parallel letter processing is thought to be a specialized mechanism for encoding location-invariant letter position that provides direct access to semantics via orthographic information alone. Sustaining this view, recent research has shown that children start identifying words fast and automatically once they have attained a certain decoding level (Karageorgos et al., 2020), and automatic and fast word reading ensures comprehension (Álvarez-Cañizo et al., 2015). Indeed, it has been highlighted that orthographic processing is a key aspect for efficient reading beyond phonological knowledge or intelligence (Deacon et al., 2019; Rakhlin et al., 2019; Rothe et al., 2015; Zarić et al., 2021).

However, this transposed-letter effect might not be specific to position coding mechanisms of orthographic stimuli but may apply to those of any kind of visual stimuli. As a first approximation to this hypothesis, Tóth and Csépe (2017) reported a transposed-character effect that remained stable across Grade 2 and Grade 4 in strings of unfamiliar characters (i.e., Armenian letter strings) as well as in digit strings (thereby suggesting that transposed-character effects are not restricted to letters) but also an increase in the transposed-character effects with letter strings (i.e., Hungarian words and nonwords). According to the adaptive specialization hypothesis proposed by the authors, their results provide support for an adaptation response of the visual system for the development of orthographic processing. Along this line, Duñabeitia et al. (2015), using the same–different matching task, reported a robust transposition cost for letter strings only in children who had acquired basic literacy skills (i.e., children were tested at the end of Grade 1).

The current investigation went beyond these studies in several ways. First, Experiment 1 replicated a transposition cost for letter strings in Grade 1—as found in Duñabeitia et al. (2015). However, the size of the letter transposition cost was similar to that of the transposition costs found in both digit strings and strings of geometrical forms in Grade 1 and Grade 2. Second, and more important, transposition cost was modulated by level of formal education (i.e., grade) only for letters, whereas this was not the case for digits and geometrical forms—as found by Tóth and Csépe (2017).

These findings fit with the accounts of Massol and Grainger (2022), who recently proposed a theoretical framework for the processing of identity and order information of different types of character strings (i.e., letter, digit, and symbol) based on previous research in adults (Massol et al., 2013; Massol & Grainger, 2022, 2024). In this framework, shown in Fig. 4, stimuli are first encoded at the level of complex feature detectors. These complex features include whole-letter and whole-digit representations as well as the complex features involved in visual object identification other than words and numbers. At this level, information regarding identity and position of each character within the string is coded and would enable the transition from location-specific to location-invariant processing. Supporting this hypothesis, we found that detecting a transposition change was harder than detecting a substitution change independently of the type of character strings for all children and adults. We interpret these findings as revealing a common effect of character transposition on processing at the level of gaze-centered complex features, reflecting a certain amount of perceptual noise due to visual feature detectors affecting positional coding of any kind of character string at any point during development.

As location-invariant processing develops, two different mechanisms are hypothesized to operate. First, a generic order-encoding mechanism operates independently of the type of stimulus. This mechanism would code precise positions of each character within a string. As illustrated in Fig. 5, the letter R is encoded at position 3, the digit 8 is encoded at position 6, and the arrow is encoded at position 2. Second, an encoding location-invariant order mechanism specific to the reading system starts processing open bigrams (i.e., bigrams provide information about contiguous and non-contiguous letters within words; see Grainger & van Heuven, 2004) as a result of the formation of orthographic representations of words. As illustrated in Fig. 5, for the bigram R–H, the position of the letter H is coded as being after the letter R in the stimulus. The current results are in line with this framework, showing that transposition costs for letters become significantly larger than those for other types of characters in Grade 3, and this difference remained significant up to Grade 5. Similar results were observed in adults (Experiment 2), revealing greater transposition costs for letters than for digits and geometrical forms. Therefore, the greater transposition cost for letters emerging at Grade 3 reflects a letter-specific, location-invariant order-encoding mechanism as a consequence of the development of orthographic representations of words.

Our data clearly reveal that literacy experience leads to the development of location-invariant encoding of letters due to parallel processing of words, which emerges around Grade 3. Based on the current results, parallel processing of letters, and therefore of a letter-specific, location-invariant encoding mechanism, is absent at the very first stages of reading acquisition.

When children have low exposure to printed words, letter position within the word is processed through the generic order-encoding mechanism that is involved in identifying any kind of character strings. Our data are in line with developmental studies showing that during the earliest stages of reading acquisition, children employ a serial letter-by-letter strategy (Grainger et al., 2016; Schubert et al., 2017) that consequently leads to rather rigid letter position coding. As children acquire some reading experience and after practicing this ordinal letter coding, parallel letter processing starts and the location-invariant orthographic code operates progressively. Critically, this transition seems to occur around Grade 3. This will optimize reading by direct access to semantics from orthographic information (i.e., open-bigram coding) (Grainger & van Heuven, 2004; Grainger & Ziegler, 2011). It should be mentioned that the nature of the reading process implies that any word identity is determined on the basis of knowledge of a subset of the word's letters and their relative positions. This is not the case for number processing, for example, where the very precise position of each digit is essential for obtaining accurate magnitude information. The coarse-grained orthographic code will be acquired only for strings of elements that can form familiar wholes, as is the case for strings of letters. This is clearly not the case for strings of geometrical forms and is likely not to be the case for digit strings given the rarity of familiar numbers such as well-known dates.

Altogether, these findings confirm our hypothesis that TL effects are driven mainly by the flexibility of orthographic processing that implements relative position coding for letter strings. The current findings also provide evidence that this orthographic code emerges only once a certain reading experience is attained.

Conclusion

The current cross-sectional investigation revealed a clear picture about the development of a letter-specific, location-invariant order-encoding mechanism during the first years of reading acquisition. Results highlighted that this location-invariant letter position mechanism emerges in Grade 3, with a greater transposition cost for letter strings than for both digit strings and strings of geometrical forms. Therefore, our outcomes support the view that whereas certain flexibility exists to process any type of string in childhood due to positional noise operating at the level of complex feature detectors, the location-invariant position mechanism for letters is a consequence of reading acquisition. These findings also have clear educational implications. Due to the importance of specific letter coding during the first years of reading acquisition, letter-by-letter reading should be encouraged to form exhaustive whole-word representations (Share, 1995). This decoding experience might ensure accurate and fast word recognition and guarantee the development of efficient invariant letter position coding mechanisms that are necessary to read words not only accurately but also automatically.

Data availability

I have shared the link to my data.

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Data availability

The authors confirm the availability of shared data. The datasets are accessible on the Open Science Framework website (https://osf.io/g5ra6).

Author contributions

Stéphanie Massol: design, programming, data analysis, and writing; **Joana Acha:** design and writing; **Lisa Rondot:** design, programming, and writing; **Marta Vergara-Martinez:** design and writing; **Emilie Favre:** design and writing; **Bernard Lété:** design, data analysis, and writing.

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jecp.2024.106081.

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