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Development of children's identity and position processing for letter, digit, and symbol strings: A cross-sectional study of the primary school years

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ABSTRACT

Letter recognition and digit recognition are critical skills for literate adults, yet few studies have considered the development of these skills in children. We conducted a nine-alternative forced-choice (9AFC) partial report task with strings of letters and digits, with typographical symbols (e.g., $, @) as a control, to investigate the development of identity and position processing in children. This task allows for the delineation of identity processing (as overall accuracy) and position coding (as the proportion of position errors). Our participants were students in Grade 1 to Grade 6, allowing us to track the development of these abilities across the primary school years. Our data suggest that although digit processing and letter processing end up with many similarities in adult readers, the developmental trajectories for identity and position processing for the two character types differ. Symbol processing showed little developmental change in terms of identity or position accuracy. We discuss the implications of our results for theories of identity and position coding: modified receptive field, multiple-route model, and lexical tuning. Despite moderate success for some theories, considerable theoretical work is required to explain the developmental trajectories of letter processing and digit processing, which might not be as closely tied in child readers as they are in adult readers.

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Introduction

For literate adults, recognizing letters occurs automatically and nearly flawlessly, yet written language depends on our domain-general systems for seeing and remembering. In the modern world, digits and symbols are also encountered and processed quickly and easily. Currently, the trajectory of the acquisition of accurate and efficient processing of these characters is not clear. In this study, we investigated character identification and position representation in primary school children and the factors that affect the development of these cognitive skills.

Although letters are usually processed within words during reading tasks, our aim in this study was to investigate the stages of identification that happen before words are read. To this end, we used strings of random letters, digits, and symbols in a partial report task where participants briefly view a string of five characters and are cued to recall the character that was present at a particular position. This task has been argued to index bottom-up processes in character identification (e.g., Grainger, Bertrand, Lété, Beyersmann, & Ziegler, 2016; Mason, 1982; Tydgat & Grainger, 2009). Using random letter strings rather than words avoids some differences between letters, on the one hand, and digits and symbols, on the other (e.g., letters are usually combined to form meaningful units, whereas digits or symbols carry meaning even when presented singly), thereby allowing a purer comparison among character types. Identification tasks with character string stimuli like these have been used in a number of studies with adults to assess processing of letters, digits, and (to a lesser extent) symbols and other two-dimensional shapes.

Adult letter and digit identification

What are the cognitive processes required to complete a partial report task? We assume that when letters and digits are presented, identification processes are automatically engaged. According to one theory, visual features of the letter/digit shape are represented and then mapped to stored visual forms and finally abstract letter and digit identities (Caramazza & Hillis, 1990; McCloskey & Schubert, 2014; Schubert & McCloskey, 2013). Another theory posits an early stage of abstract letter/digit detectors, followed by two types of representations for letters: one in which position is coded coarsely and another in which position is coded more precisely (Grainger, Dufau, & Ziegler, 2016). Both theories contend that the highest representations are location invariant; that is, they indicate the presence of a letter independent of its location in the visual field. Although the partial report task could be successfully completed by matching the response options to early visual representations (i.e., visual features or letter/digit detectors) of the stimulus, it is commonly assumed that processing continues throughout the identification system unless disrupted (e.g., masked presentation). Accordingly, we consider that the results obtained in this task are relevant to understanding the representation of location-invariant abstract letter and digit identities.

Because position is cued only after stimulus offset, participants must represent the stimuli in all positions. (Note that this does not imply uniform accuracy for all positions, but a floor effect at particular positions might suggest a failure to attend to all positions.) The most common string length for studying these character identification processes is five because this allows examination of string positions with different properties. Initial and final positions (1 and 5, respectively) can be distinguished from medial positions (2–4). Furthermore, fixation is generally on the central position (3), allowing for contrasts between the fixated medial position and nonfixated medial positions (2 and 4).

When adults are asked to report letters and digits presented in such a manner, a W-shaped accuracy function across serial positions is often obtained (see Fig. 1A for an example). This pattern reflects high accuracy at the central, initial, and end positions and reflects lower accuracy at medial nonfixated positions (e.g., Collis, Kohnen, & Kinoshita, 2013; Hammond & Green, 1982; Mason, 1982; Tydgat & Grainger, 2009). In contrast to this W shape found for letter and digit accuracy, the pattern found with symbols is reported as a V shape (Hammond & Green, 1982; Tydgat & Grainger, 2009) or a flat (or very shallow W-shaped) serial position function (Collis et al., 2013). A number of explanations have been proposed to explain the accuracy discrepancies across positions for character strings. For example,

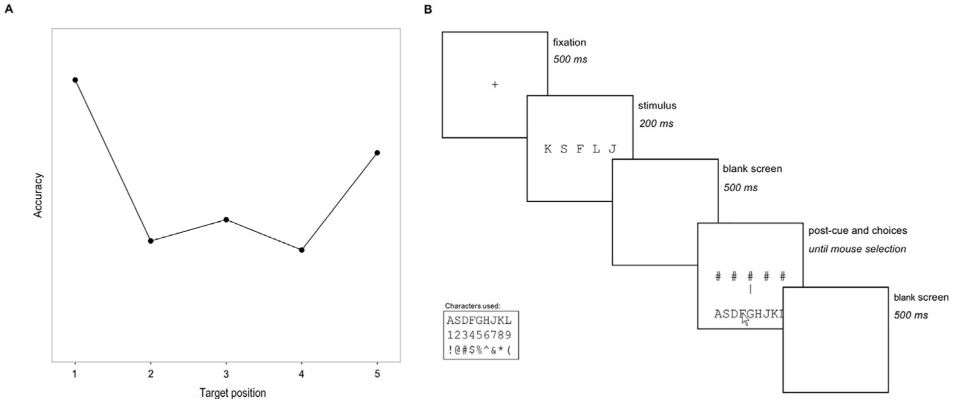

Fig. 1. (A) Typical serial position function for adult readers in a partial report task with letter strings. (B) Schematic of the partial report task we used showing a letter trial.

greater accuracy for the outer positions in the string is explained by less visual crowding (i.e., excessive integration of visual features from nearby visual objects) in these positions because these items have only one neighboring element (Chanceaux & Grainger, 2013). Furthermore, accuracy at the central position may be attributed to the acuity benefit in foveal vision (Marzouki & Grainger, 2014). However, these general visual constraints would apply at a very low level of representation and should affect all types of character strings—letters, digits, and symbols. Accordingly, to explain the difference between letter/digit strings, on the one hand, and symbol strings, on the other, distinct or additional factors must influence processing of some character types.

One account of identification performance for letter and digit strings has been proposed by Tydgat, Grainger, and colleagues (Chanceaux & Grainger, 2012; Chanceaux, Mathôt, & Grainger, 2013; Grainger, Dufau, et al., 2016; Tydgat & Grainger, 2009). They proposed the modified receptive field (MRF) hypothesis to explain the prominence of the initial-position advantage for letters and digits and the overall W shape. They posited that the gaze-centered receptive fields used for letter and digit identification (letter/digit detectors) by adults are shrunk and elongated to the left (in the left visual field). This leftward elongation exaggerates the lack of crowding for the initial letter (which has no leftward flanker), increasing identification accuracy at this position. A standard round receptive field is assumed for symbols (which are much less often encountered, particularly in strings), resulting in a qualitatively different accuracy pattern for these characters. In addition to explaining the adult serial position pattern for letters and digits, the MRF hypothesis also makes predictions for the developmental trajectory of character identification.

Development of letter identification

The MRF hypothesis predicts a change in the serial position function for letter strings as children become fluent readers. The authors proposed that as children learn to read, receptive fields are modified to reduce crowding among letters and digits in strings and to give priority to processing of the first letter in words (Grainger, Bertrand, et al., 2016). This leads to a change in the gaze-centered receptive fields used for letter and digit identification, shrinking them overall and elongating them to the left (in the left visual field). However, currently it is somewhat unclear what precise factors drive the modification of the receptive fields. For example, is it an increase in entries in the orthographic lexicon, amount of exposure to print, or sophistication of parallel relative to serial (decoding) reading processes? Grainger, Bertrand, et al. (2016) stated that "changes in preferred viewing location and changes in receptive field size both would be driven by the developing reader's aim to more efficiently process orthographic information via parallel letter processing" (p. 168). However, what is the source of the reader's aim to engage in parallel processing, and what information does the reader possess indicating that this will result in more efficient orthographic processing? Although this hypothesis makes a developmental claim—receptive fields (and hence letter/digit identification accuracy) change as children progress toward adult-level reading fluency—it is unclear what other aspects of development should be related to this outcome. In addition, although the level of processing at which the MRF hypothesis operates is also used for recognition of digit strings (Grainger, Dufau, et al., 2016), the impact of experience with digits and number reading has not been considered.

Few studies have investigated children's processing of character strings in partial report tasks to shed light on the development of letter and digit identification. Ziegler, Pech-Georgel, Dufau, and Grainger (2010) conducted a two-alternative forced-choice (2AFC) partial report task with letter, digit, and symbol stimuli. The children in their study (with average reading abilities for their age) showed comparable effects for letters and digits, with a distinct position function for symbol strings, as has been reported in the adult literature. In another study, Grainger, Bertrand, et al. (2016) investigated children's processing of letter strings specifically, comparing them with common shapes (e.g., heart, crescent, circle). The participants in this study were children in Grades 1 to 5. The authors' findings are consistent with the MRF hypothesis in that accuracy for the first position (and no other positions) in letter strings improved as children's reading age (based on the Alouette reading fluency test) and chronological age increased, whereas first position accuracy did not improve differentially for shapes. Final position accuracy did not improve in either condition. However, it should be noted that when the analyses were based on the entire sample of children, including some whose overall accuracy on the task was not above chance, first position and third position accuracy increased with reading age for both letters and symbols. Beyond these studies, no other studies have presented serial position data for children, leaving open a number of questions about how identification processing for letter, digit, and symbol strings develops.

Position coding: Where is the L in KSFLJ?

The serial position function across character strings and the MRF hypothesis focus on processing of identity information. However, successful reading also requires processing the position of each character within a string, for example, to distinguish *smile* from *slime*. Partial report tasks vary in whether position information is needed to perform accurately. For example, partial report tasks that are free response (e.g., Marzouki & Grainger, 2014) require position processing to prevent errors such as reporting J when asked to report the element in the third position in KSFLJ. Tasks with a 2AFC response may require position processing, depending on the alternatives that are used. If the distractor item is present elsewhere in the string (Collis et al., 2013; Grainger, Bertrand, et al., 2016; Hawelka, Huber, & Wimmer, 2006; Tydgat & Grainger, 2009, Experiments 5 and 6), position information must be used to distinguish between the responses. However, if the distractor (or the probe for probe present/absent tasks) is not present in the string (Hammond & Green, 1982; Mason, 1982; Tydgat & Grainger, 2009, Experiments 1–4; Ziegler et al., 2010), this is not required. Therefore, the type of partial report task used affects the information needed to perform accurately, and a partial report task with particular properties allows us to investigate not only identity processing but also position processing.

Of the studies employing a partial report task that permits examination of position errors, Tydgat and Grainger (2009) were the first authors to adopt a nine-alternative forced-choice (9AFC) post-cued paradigm. In this task, the response choices included all characters used in that condition, including the five present in the stimulus on any given trial. Accordingly, participants could select the correct character or make one of two types of errors. Errors could be selection of a character from another position in the string (e.g., reporting L at position 3 for the stimulus KSFLJ) and of an intruding character that was not present at all (e.g., reporting H at position 3 for the stimulus KSFLJ). These two types of mistakes reflect errors in representing the position of the characters in the string and in representing the identities, respectively. Position errors are assumed to reflect a misattribution of character position rather than a misidentification of the character at the cued position (Collis et al., 2013; Tydgat & Grainger, 2009). Tydgat and Grainger (2009) calculated performance when only position errors were considered as errors and found that the proportion of position errors differed by character type (letters, digits, or symbols) and by position in the string and that these two variables interacted. A graph of the results displays W-shaped performance for all three character types, with overlap at positions 2, 3, and 4, but higher accuracy at outer positions for letters and digits. However, these possible differences were not tested directly, and no further analyses were conducted.

Collis et al. (2013) employed a similar 9AFC partial report task that also allowed for analysis of position processing. The identification accuracy performance found for participants without dyslexia was a W shape for letter and digit strings and a shallower W-shaped function for symbol strings (see Fig. 1A for a schematic representation of the pattern for letters and digits). Collis and colleagues analyzed position errors differently from Tydgat and Grainger (2009), instead calculating the proportion of errors at a given position that were position errors. This analysis revealed high accuracy (low proportions of position errors) at the initial and final positions of the string for letter and digit strings for all participants and revealed more position errors at medial positions 2 and 4 (Collis et al., 2013).

Overall, Collis et al. (2013) study provides an important snapshot of position processing in adult readers to which our data from young readers can be compared. The task used in our study is a close adaptation of that used by Collis and colleagues. Therefore, we treat their adult data as a depiction of the target reading system being acquired by young readers; we qualitatively compare the developmental patterns for letters, digits, and symbols with the adult serial position functions obtained in their study.

Development of letter position processing

Research into the development of adult-like position processing has focused mainly on letters, and the existing theories of the development of position coding pertain solely to letter position. Although there is broad agreement that letter position processing abilities differ between adults and children, the direction of developmental change is debated. There are two main theories concerning the development of position processing during reading acquisition. One theory, the multiple-route model (MRM) by Grainger and colleagues (Grainger, Lété, Bertand, Dufau, & Ziegler, 2012; Grainger & Ziegler, 2011; Ziegler, Bertrand, Lété, & Grainger, 2014) contends that letter position coding begins very strictly, with precise assignment of each letter to its position, and becomes looser as reading acquisition progresses. The MRM suggests that children initially engage in serial processing of letters and with experience begin to develop parallel processing of letter strings. Along with this parallel processing, children begin to represent letter position through open bigrams, representations that code for both identity and coarse-grained position (Grainger et al., 2012). This theory is supported by results showing that the facilitatory effect of primes that differ only in letter position (e.g., *talbe* for *table*) increases as children progress through school (Grade 3 vs. Grade 5: Lété & Fayol, 2013; Grades 1–5: Ziegler et al., 2014).

However, other studies have identified the opposite empirical pattern, with interference from primes that differ only in letter position *increasing* with age (Grade 3 vs. Grade 6: Acha & Perea, 2008; Grade 3 vs. Grade 5: Castles, Davis, Cavalot, & Forster, 2007). In accordance with this second pattern, Castles et al. (2007) posited the theory of lexical tuning, where position coding becomes stricter as children acquire a larger orthographic lexicon (Castles et al., 2007; Kezilas, McKague, Kohnen, Badcock, & Castles, 2017). Castles et al. (2007) proposed that due to the overlap in letters across different English words—particularly shorter words that children acquire early—knowing more words requires more precise positional representation of the input to distinguish *cat* from *act* and to distinguish *smile* from *slime.* (A similar prediction was made for identity processing, with reading development thought to prompt improvement of letter identification to distinguish lexical entries differing in one letter identity such as *fact* and *face* [Castles et al., 2007].) Currently, both theories of letter position development—MRM and lexical tuning—have garnered some empirical support, and it remains to be seen which better captures positional processing across reading acquisition.

Both of these theories focus on letter position processing without explicit claims for development of position processing for digits or symbols. In addition, the majority of the relevant empirical data come from lexical decision and reading-aloud tasks, which are limited to letter stimuli. Therefore, the generalizability of these theories and their implications for other character types (digits and symbols) are not clear. As mentioned previously, some effects on character processing may be domain-general visual constraints (e.g., crowding, acuity), whereas the MRM and lexical tuning hypotheses deal in predictions for letter processing specifically.

The current study

Our study investigated children's development of character identity and position processing with a partial report task. The 9AFC partial report paradigm has a number of advantages for addressing the questions at hand. First, it indexes primarily bottom-up processing, separating identity and position coding of letters and digits from later stages such as lexical access (for words). Second, because all response choices are displayed during response selection, effects of stimulus familiarity across the character types—although not avoided entirely—are mitigated. (Nonetheless, some differences remain; for example, random digit strings are interpretable as multidigit numbers, whereas random letter and number strings are not interpretable. This point is taken up in the Discussion.) Thus, this paradigm allows for reasonable comparison across character types. Finally, it allows us to analyze position errors separately from identity errors.

As a first step, we established the general pattern of accuracy for letters, digits, and symbols across the five string positions. Separately, we did the same for the pattern of position errors—the proportion of errors that are reporting another character from the stimulus string. Our analyses addressed two main questions regarding the development of character identification and position-coding processes. First, how does the processing of letter, digit, and symbol strings change with increasing grade? Second, how does position coding, indexed by the proportion of position errors, change with increasing grade?

Across the identity and position analyses, predictions can be drawn from the theoretical background on letter identity and position coding development—the MRF hypothesis and the MRM and lexical tuning hypotheses. According to the MRF hypothesis, receptive field modification occurs for letters and digits as reading acquisition progresses. Accordingly, we should see an increase in the initial-position advantage for letters and digits across grade and a smaller or nonexistent increase for symbol strings. For position processing, the MRM theory predicts that position errors will increase over development, whereas the lexical tuning hypothesis predicts that position errors will decrease. However, both of these predictions are for letter position coding, and their extension to the partial report task and digit and symbol processing is novel. At a coarse-grained level, evidence for a decrease in the proportion of position errors is consistent with the lexical tuning theory, whereas an increase in the proportion of position errors is consistent with the MRM theory.

Method

Participants

A total of 69 children, recruited from the metropolitan area of Sydney, Australia, participated in this study. The study was conducted as part of the SKIDS (Sydney Kids Intellectual Development Study) day-long holiday research program at Macquarie University; along with the tasks described below, the children participated in additional independent research experiments. Parental consent was obtained prior to each child's participation.

Experimental task: Partial report

The strings presented consisted of five letters, digits, or symbols, with each character within the string separated by a single character space. Nine characters from each of the three categories were used (drawn randomly without replacement): 1, 2, 3, 4, 5, 6, 7, 8, 9; A, S, D, F, G, H, J, K, L; and !, @, #, $, %, ^, &, ∗, (. Participants were presented with a fixation cross (500 ms), followed by a five-character string in the center of a computer screen for 200 ms, which was replaced by a blank screen (500 ms) and then a post-mask (five ? symbols) and post-cue (vertical bar: |) below one of the five string positions until response. Along with the mask and post-cue, this screen displayed the nine response options. Participants selected their response by clicking on the appropriate character. A 500-ms blank screen intervened between each trial. See Fig. 1B for a schematic trial in the letter condition as well as the nine letters, digits, and symbols used. Characters were presented in Courier New font in black text on a white background. Each individual character subtended .57 × .92 degrees of visual angle (width × height), for a total string width of 4.8 degrees. This task was adapted from Collis et al. (2013); changes to the original paradigm were to increase the presentation duration for the child participants (duration determined through pilot testing), alter the response mode to mouse selection rather than key press, and convert the experiment to presentation via MATLAB release R2012b (The MathWorks, Natick, MA, USA) using PsychToolbox version 3.0.10 revision 3187 (Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

Each child completed 120 trials of the experiment: 40 trials each of the three character types consisting of 8 trials testing each of the five positions. All three conditions were presented intermixed across four blocks, with short breaks in between. Motivational feedback was provided and was unrelated to task performance. The experiment was preceded by a familiarization phase in which an experimenter explained the task to the child and walked through at least one example trial in which each screen event (e.g., fixation, stimulus, post-cue) was advanced manually.

Reading profile

All participants completed the Castles and Coltheart test of single-word reading aloud (CC2; Castles et al., 2009a). This test includes regular words, irregular words, and pseudowords that are presented intermixed and increase in difficulty as the test progresses; the full test contains 40 items of each category. Each category of items is scored (and discontinued) separately. We used the average of the *Z* score obtained for irregular words and pseudowords, indexing the functioning of lexical and sublexical processing, respectively (Castles et al., 2009b) as a measure of reading proficiency.

Analyses

The data were analyzed using logistic mixed effects modeling implemented in R version 3.3.1 (R Core Team, 2016) with the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015). Two dependent variables were investigated: response accuracy and proportion of position errors. For each trial, the response was classified as a position error if the response was incorrect for the cued position but present at another position in the string (e.g., stimulus: HGSLA, position 2 cued; response: L). The *Z* and *p* values were estimated using the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2016), and *p* values less than .05 were considered significant. Data visualization was accomplished with the *ggplot2* package (Wickham, 2009).

Random intercepts for items and participants were included; more complex random effects terms resulted in model nonconvergence. Fixed effects were included for the variables of interest and their interactions. All models included character type (categorical factor with three levels: letters, digits, or symbols) and target position (categorical factor with five levels: position 1, 2, 3, 4, or 5). For target position, position 3 (the center of the string and the location of fixation) was set as the reference level, and comparisons are reported between this position and the other positions. As the first step of analysis, a base model was created with these factors only to describe the average performance of the entire sample. Further analyses tested specific hypotheses by adding to this base model the fixed factor of grade (continuous and centered).

Model fit was evaluated using Akaike's information criterion (AIC), a metric that takes into account both model fit and model complexity and indexes the distance from a hypothetical ideal model (Burnham & Anderson, 2002). A smaller AIC value indicates a better fit of the model to the data. It should be noted that the absolute size of the AIC is not interpretable; only the relative difference between the AIC of two models ($\Delta_{\text{Model2}} = AIC_{\text{Model1}} - AIC_{\text{Model2}}$). In cases of nested model comparison (i.e., comparing Model 1 and Model 2 where the predictors of Model 1 are a subset of the predictors of Model 2), a chi-square test was used to evaluate the models (using the "anova()" function from *lmerTest* with all default parameters).

Results

Final participant sample

Of the 69 children who completed the study, 12 were excluded from the results presented here. Of these, 7 children were excluded for not performing the experimental task properly, which was indexed by a pattern in the letter condition of high accuracy on the first position (≥50%) and chance accuracy on the remaining positions (≤12.5% correct, chance = 11%). A further 5 children were excluded for averaging below-chance performance across all positions in the letter condition. Because the letter condition is expected to be the easiest due to higher familiarity with the letter stimuli than digit or symbol stimuli, these cutoffs were reasonably conservative.

Thus, 57 children were retained for further analysis. The children in the retained sample ranged in age from 6;11 (years;months) to 11;11, corresponding to Grade 1 through Grade 6 students in the school system of New South Wales, Australia. Note that there is a mandatory pre-Grade 1 school year (‘‘kindergarten”) during which children receive formal instruction in literacy and numeracy. Hence, our participants had attended school for between 2 and 7 years. There were 4 students in Grade 1, 16 in Grade 2, 16 in Grade 3, 14 in Grade 4, 5 in Grade 5, and 2 in Grade 6.

A wide range of reading abilities were represented, with *Z* scores on our single-word reading measure ranging from −2.17 to 1.67. Classifying the children based on standard cutoffs for normal performance ($-1 < Z < 1$) revealed that the majority of the children (40 of 57) had average reading abilities for their age, 6 had below-average reading, and 11 had above-average reading. No relationship was observed between CC2 reading score and exclusion due to poor task performance.[1] The raw data (including by-trial performance for the entire participant sample and age, grade, and CC2 scores) are available at https://osf.io/mjqv5/ on the Open Science Framework.

Reading performance

Although we had intended to use CC2 scores to predict performance on the partial report task, comparisons of the grade-based models and the CC2-based models indicated that the grade-based models had a superior fit to the data. For the identity accuracy measure, the grade model had a smaller AIC than the CC2 model, indicating a better fit to the data ($AIC_{\text{ACCCC2}} = 7467.1$, $AIC_{\text{ACCGrade}} = 7449.0$, $\Delta_{\text{AccGrade}} = 18.1$). Likewise, for the position error data, the grade model is also preferred to the CC2 model ($AIC_{\text{POSCC2}} = 9169.1$, $AIC_{\text{POSGrade}} = 9129.2$, $\Delta_{\text{POSGrade}} = 39.9$). For completeness, the CC2 model results can be found in the Appendix.

Accuracy by character type and position

The base model describes the shape of the serial position functions for letters, digits, and symbols. It does not take into account grade and so provides only a snapshot of the average performance of the children in our sample. These data are plotted in Fig. 2.

The base model shows no overall differences among the letter, digit, and symbol conditions (*ps* > .68) but shows particular positional advantages for letters and digits. Within the letter condition, there was an accuracy advantage for the outer positions, with both position 1 and position 5 more accurate than position 3 (initial-letter advantage: $\beta = 1.45$, $SE = 0.15$, $z = 9.65$, $p < .0001$; final-letter advantage: $\beta = 0.70$, $SE = 0.15$, $z = 4.63$, $p < .0001$). The initial-position advantage was also found for digit strings (initial-digit advantage: $\beta = 1.25$, $SE = .015$, $z = 8.26$, $p < .0001$). No initial-position advantage was found for symbol strings ($p = .94$).

The end-position advantage was not found in digits or symbols (digits: $p = .20$; symbols: $p = .47$). Although symbols did not show an initial- or end-position advantage, they did show a fixation

[1] Of the 7 children excluded for not following instructions, 2 had above-average CC2 reading scores and 5 had average reading scores. Of the 5 children excluded for below-chance performance, 1 had above-average CC2 reading score, 2 had average reading scores, and 2 had below-average reading scores.

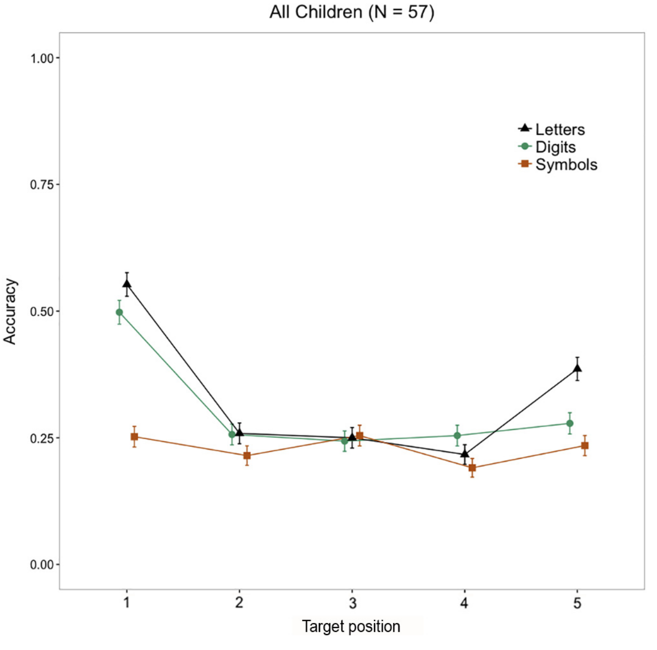

Fig. 2. Identification accuracy by string position and character type collapsed across all participants.

advantage relative to position 4 ($\beta = -0.40$, $SE = 0.17$, $z = -2.41$, $p = .02$). This advantage was smaller than the fixation versus position 4 difference in digits ($\beta = -0.47$, $SE = 0.23$, $z = -2.02$, $p = .043$).

In summary, accuracy in both the letter and digit conditions showed an initial-position accuracy advantage relative to fixation. Letter accuracy also displayed an end-position advantage, creating a U-shaped serial position function. The only differential effect by position in symbol strings was lower accuracy at medial position 4 than fixation.

Effect of grade on identity accuracy

With this analysis, we asked how the serial position function for accuracy changes as children advance in school. Grade serves as a rough metric for amount of exposure to printed materials as well as for reading proficiency. According to the MRF hypothesis, receptive field modification occurs as children gain experience with letter and digit strings. Therefore, we would predict an increase in the initial-position advantage for letters and digits for older children and a smaller or nonexistent increase for symbol strings. Another key aspect is the relationship between identity and position processing. A number of studies have suggested that children's letter identity skills develop earlier than their letter position skills (Castles et al., 2007; Kezilas et al., 2017; Kohnen & Castles, 2013), leading to the prediction that accuracy will be relatively high, even for fairly young participants, and may increase only slightly with age.

All effects in the accuracy base model were maintained in the grade model for letters, digits, and symbols. This suggests that the general effects described in the previous section accurately reflect performance regardless of grade. However, the model also revealed grade-related effects in the letter and digit string conditions. These data are presented in Fig. 3, split into three grade groups (Grades 1 and 2, Grade 3, and Grades 4, 5, and 6) with approximately equal *numbers of participants*. Adding grade as a predictor to the base identity accuracy model results in a smaller AIC ($AIC_{\mathrm{ACCBase}} = 7466.1$, $AIC_{\mathrm{ACCGrade}} = 7449.0$, $\Delta_{AccGrade} = 17.1$), $\chi^2(df = 15) = 47.13$, $p < .0001$. In addition, grade interacted with position in the letter condition; although both the initial position and fixation position increased in

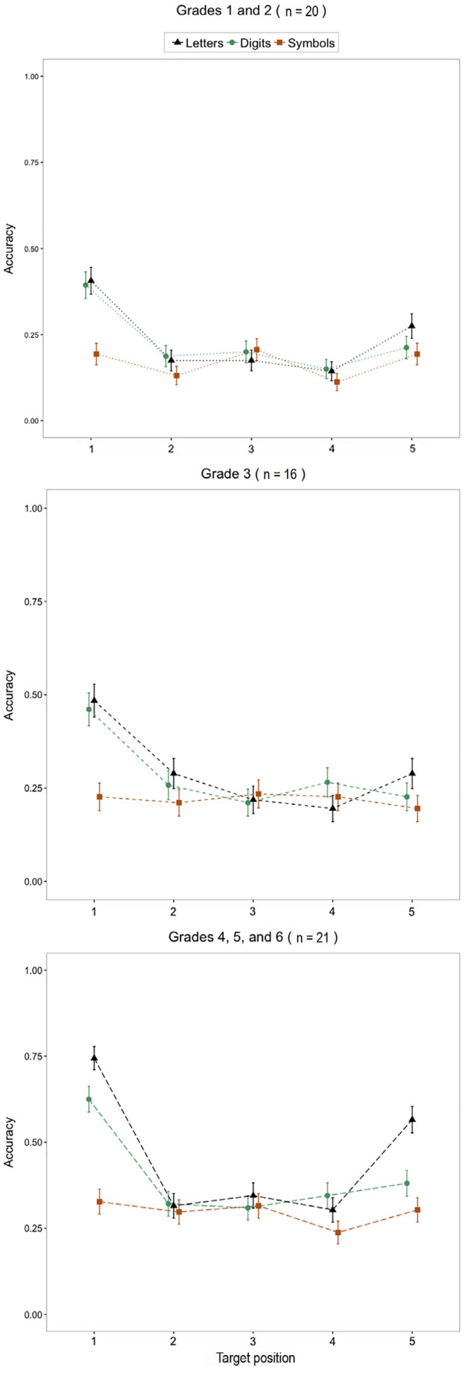

Fig. 3. Accuracy by string position and character type across three grade groups: Grades 1 and 2 (20 participants), Grade 3 (16 participants), and Grades 4, 5, and 6 (21 participants). Groupings are for display purposes only; analyses considered grade as a continuous variable.

accuracy with grade, the initial position increased to a greater extent ($\beta = 0.31$, $SE = 0.13$, $z = 2.36$, $p = .018$). In digits, there was also a positive effect of grade, with higher grade associated with higher overall accuracy ($ACC_{Grade1} = .19$, $ACC_{Grade6} = .55$), $\beta = 0.25$, $SE = 0.11$, $z = 2.24$, $p = .025$. However, grade did not interact with position. In symbols, there was no effect of grade on accuracy ($p = .086$) overall or for any position.

Proportion of position errors by character type and position

In this version of the base model, the dependent variable is the proportion of position errors made at each position for each character type. Our paradigm allowed for analysis of the proportion of errors that were reporting an item from another position in the string such as reporting F when cued for the fourth position of the string KSFLJ. Analysis of the proportion of position errors reveals children's specific abilities in position coding; incorrect letter identity or position coding could lead to an error as considered in the previous analyses (i.e., poor accuracy), but the combination of correct letter identity information and imprecise position information will result in a position error.

Fig. 4 presents these data in graphical form. In the statistical model, there were no overall differences among the letter, digit, and symbol conditions ($ps > .14$). However, letters and digits show an initial-position advantage relative to the fixation position (letters: $\beta = -1.17$, $SE = 0.14$, $z = -8.07$, $p < .0001$; digits: $\beta = -0.76$, $SE = 0.14$, $z = -5.43$, $p < .0001$). In this case, the advantage refers to a *decrease* in position errors rather than to an increase in accuracy. Despite the presence of this initial-position effect in both character types, the advantage is larger for letters than for digits ($\beta = 0.40$, $SE = 0.20$, $z = 1.99$, $p = .046$), perhaps due to a numerically higher value for letters at fixation. The initial-position advantage is not found for symbols ($p = .14$). Furthermore, letters (only) showed an end-position advantage, with fewer position errors at position 5 than at fixation ($\beta = -0.55$, $SE = 0.14$, $z = -4.03$, $p < .0001$; digits: $p = .06$; symbols: $p = .14$). Symbols showed no differential effects by position.

In summary, letters showed a reduction in position errors at the outer positions relative to fixation. The initial-position advantage was also present for digits, but no differential position effects were present for symbol strings. These analyses of accuracy and position errors provide only an overview of the performance by primary school-age children. In the following sections, we address the development of identity and position processing more directly by observing the changes across grades in school.

Effect of grade on proportion of position errors

In this analysis, we asked how the proportion of position errors made at each position of the string was related to grade in school. There are two opposing views in the literature on the development of letter position processing. The MRM theory predicts that position errors will increase over development, whereas the lexical tuning hypothesis predicts that position errors will decrease. However, both of these predictions are for letter position coding rather than for digit or symbol coding.

As for accuracy, adding grade to the base position error model improves the model, as seen in a reduced AIC ($AIC_{POSBase} = 9156.3$, $AIC_{POSGrade} = 9129.2$, $\Delta_{POSGrade}$ 27.1), $\chi^2(df = 15) = 57.13$, $p < .001$. These results describe the developmental trajectory of accurate position coding for the three character types (see Fig. 5).

All effects in the position base model were preserved in this model for letter, digit, and symbol strings. Effects of grade on the proportion of position errors were found for letters and digits but not for symbols. In letter strings, higher grade was associated with fewer position errors overall ($\beta = -0.16$, $SE = 0.08$, $z = -1.97$, $p = .049$. Furthermore, grade interacted with position in letters; at higher grades, the difference in the proportion of position errors between final and fixation positions was reduced, with the final position having a relatively lower proportion of position errors at higher grades ($\beta = -0.24$, $SE = 0.12$, $z = -2.00$, $p = .046$).

The proportion of position errors for digits was also associated with grade differentially across the string. Grade affected the difference between the initial position and fixation ($\beta = -0.40$, $SE = 0.12$, $z = -3.32$, $p = .0009$; increasing grade led to a larger difference in position errors, with fewer at the initial position. Grade also affected the difference between position 4 and fixation ($\beta = -0.33$, $SE = 0.11$,

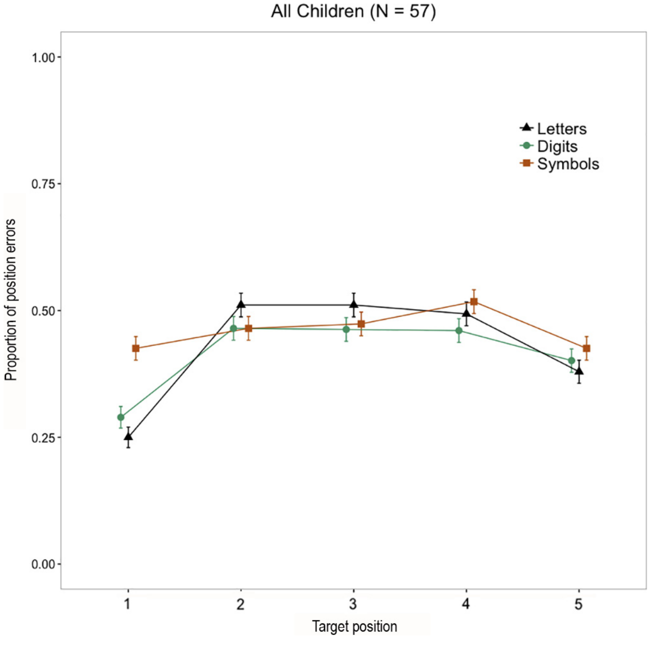

Fig. 4. Proportion of position errors by string position and character type collapsed across all participants.

$z = -2.94$, $p = .003$. This effect was in the direction that increasing grade led to a steeper decline in position errors at position 4. Finally, grade was found to affect the difference between the final position and fixation ($\beta = -0.34$, $SE = 0.11$, $z = -2.95$, $p = .003$), such that increasing grade led to a faster decrease in position errors at the final position. In summary, increasing grade led to fewer position errors overall and specifically at initial, final, and medial (position 4) positions for digit strings. In symbols, there was no effect of grade overall ($p = .95$) or for any particular positions.

In sum, effects of grade on the proportion of position errors were found for letter and digit strings. As grade increased, the overall rate of letter position errors decreased, particularly at the final position (relative to fixation). The rate of digit position errors also decreased, particularly at outer positions and position 4 (relative to fixation). No effects of grade were found on symbol position errors.

Discussion

This study investigated identity and position processing for letter, digit, and symbol strings in school-age children. Using a 9AFC partial report task, we reported accuracy and error type data from 57 children spanning primary school: Grade 1 through Grade 6. Analyses reveal the development of identity processing and position coding.

Accuracy: Development of identity processing

In the accuracy base model, which does not consider grade, differences in performance were found for the three character types across the five string positions. The lack of overall difference among the letter, digit, and symbol conditions is consistent with general visual constraints operating for all stimulus types, resulting in similar performance. However, looking at particular positions, letters showed an accuracy advantage for the outer positions relative to fixation, and digits showed an accuracy advantage for the initial position relative to fixation; similar initial and final advantages were found for both character types in adult participants. Symbols showed an accuracy advantage for fixation

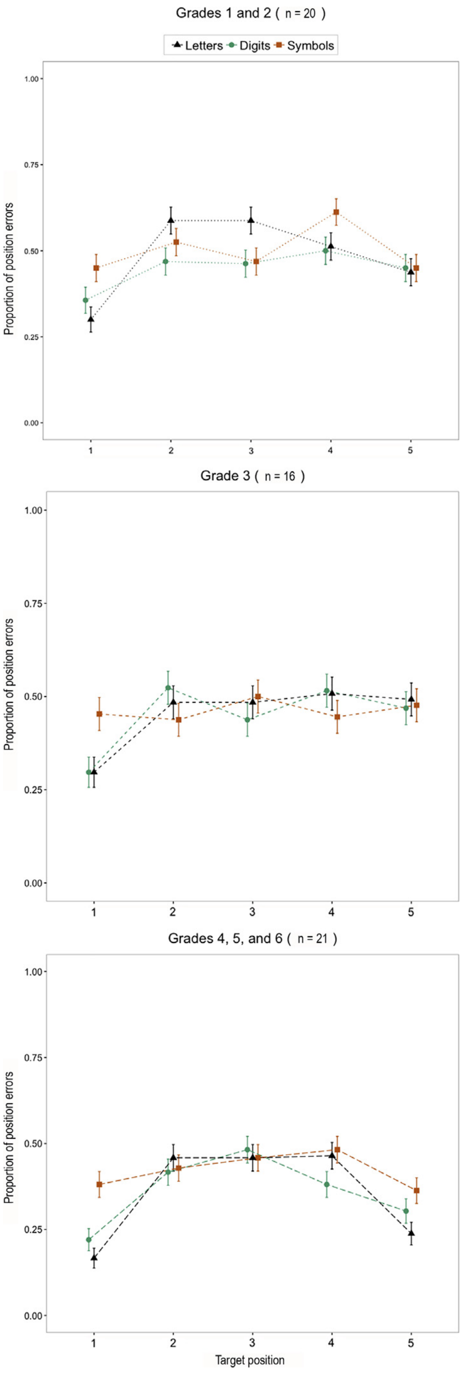

Fig. 5. Proportion of position errors by string position and character type across three grade groups: Grades 1 and 2 (20 participants), Grade 3 (16 participants), and Grades 4, 5, and 6 (21 participants). Groupings are for display purposes only; analyses considered grade as a continuous variable.

relative to a medial position (position 4). This snapshot of the identity accuracy data already gives an indication that letter processing and digit processing do not develop in tandem, although letter and digit identification processes in adults are thought to be overlapping.

From these data, we can make a rough comparison with the performance by adults in Collis et al. (2013) study where a highly similar task was used. Adults (without dyslexia) in their study produced a W-shaped accuracy curve across positions for letters and digits, with highest accuracy at the outer positions (1 and 5) and at fixation (position 3). Our child sample showed a similar pattern for letters, although without the strong fixation advantage. For digits, on the other hand, only an initial-position advantage was found, producing more of an L shape than a W shape. This lack of end-position advantage is in contrast to the predictions of the MRF hypothesis, which posits that digit processing and letter processing both are affected by receptive field tuning and should show comparable positional effects (Grainger, Bertrand, et al., 2016; Grainger, Dufau, et al., 2016).

Identification accuracy changes with schooling

The grade analysis revealed developmental changes in accuracy for letter and digit strings but not for symbol strings. This broad pattern is consistent with theories positing that letters and digits undergo a similar identification process, whereas symbols are subject to different processes. However, the specifics of the relationship between accuracy and grade also revealed differences between letters and digits; whereas letter strings showed an increasing initial-position and fixation-position advantage as grade increased, accuracy for digit strings increased across all positions without distinction.

The development of the initial position advantage for letters across grades is consistent with a recent study using a similar task (Grainger, Bertrand, et al., 2016). In that task (2AFC with the distractor being a neighboring item from the string), primary school children showed an increase in the initial-letter advantage across grades and no concurrent advantage in first-position processing for strings of simple shapes. Grainger, Bertrand, et al.'s (2016) results are consistent with the MRF hypothesis, which predicts increasing initial position accuracy for letters.

A benefit of our study is the inclusion of digit stimuli, allowing for direct comparisons between letters and digits. The MRF hypothesis states that the initial-position advantage for letters and digits should increase in parallel over the course of reading acquisition as receptive fields are elongated toward the left. Our data do not support this hypothesis, instead indicating that although a first-position advantage exists for young readers for both letters and digits, the letter advantage continues to increase throughout primary school. We found no positional advantages in the digit condition associated with school grade and instead found an overall increase in accuracy. The large range of grades in our study (Grade 1 to Grade 6), as well as the finding of a developmental change for letter strings, suggests that we had sufficient power to detect such an effect in digits if it were present. Accordingly, the MRF hypothesis's prediction of similar developmental changes for letter and digit receptive fields is not supported.

Position errors: Change in the precision of position coding

In addition to accuracy, we investigated the proportion of position errors made at each position. Whereas a correct response indicates accurate identity and position information, a position error indicates accurate identity information but incorrect position information. These errors were first analyzed in the base model, which does not include grade as a predictor. As with the identity model, no overall differences were found among the three character types. However, we found that letters and digits had fewer position errors at the initial position than at fixation and that letters also had fewer position errors at the end position. Symbols, on the other hand, showed no differential effects across the string. As was found with accuracy, letters and digits differed in the serial position function across the string, furthering the conclusion that letter processing and digit processing are not as closely tied during childhood as they are in adult readers.

Furthermore, our findings underscore the difference reported in the adult literature between letter/digit processing and symbol processing (Collis et al., 2013; Hammond & Green, 1982; Tydgat & Grainger, 2009). Strings of multiple symbols (e.g., &$!@#, as opposed to mixed strings such as $43 and @gmail) are encountered less often than letter and digit strings, particularly by children, which may lead to imprecise coding of symbol position. Random letter strings (e.g., KSFLJ) are also not often encountered, whereas digit strings are common visual stimuli and perfectly interpretable (e.g., 13752 might be a telephone number, a postal code, or the number thirteen thousand seven hundred and fifty-two, depending on context). These observations may have led to a prediction that digit position coding would be most precise given that digit strings need to be distinguished from strings with a change only in position (e.g., 37521 vs. 32571) to preserve their meaning. However, contrary to this intuitive account, high positional precision for digits was found only at the initial position.

As with the identity data, the position data can be compared with those found by Collis et al. (2013). Adult readers in their study displayed an M-shaped curve across positions for both letters and digits, with low rates of position errors at outer and fixation positions and a flatter curve for symbols. The outer-position advantage (fewer position errors) for letters found in our data is consistent with the adult data, although the lack of end-position advantage for digits is inconsistent. Position processing for digits is not often discussed, and theories of letter position development tend not to address digit position. Accordingly, our results do not conform to any existing theory but constrain future theories of digit position processing; children show an early protection from position errors at the initial position for letters and digits, but for digits the final-position advantage is not yet present.

Position coding changes with schooling

To investigate the developmental track of position coding, we added a predictor of school grade to the above model. This model revealed an effect of grade on the proportion of position errors in letter and digit strings only. The proportion of position errors for letters and digits decreased with grade, with particular improvement at the final position for letters and the initial medial position (4) and final positions for digits. These changes suggest that digit position coding improves with grade in school, as does letter position coding. Comparing these data with the adult pattern of outer-position advantage for both letters and digits, letters appear to have a head start on the development of the initial-letter advantage, whereas for digits it arises over the course of primary schooling. As in the base model, symbols were not affected by position in the string or by grade.

The two theories of the development of position coding, MRM and lexical tuning, refer specifically to letter position and predict decreased and increased precision of position coding, respectively. Higher precision of position coding should result in a decrease in position errors, whereas lower precision should result in an increase. The decrease in the number of letter position errors that we observed is consistent with the lexical tuning hypothesis—better precision of position coding over the course of reading development. This pattern is not consistent with the MRM theory, which posits that position coding loosens over development, which would lead to more position errors as grade increased.

These theories make predictions about position errors and the development of position coding for letters only, not digits and symbols. Considering the MRM theory, the source of the change in position precision is a shift to the use of open bigram representations that are letter specific. The lexical tuning hypothesis also does not make any predictions about digit position coding as it concerns the influence of lexical access on letter position coding.

Our results describe developmental change in position coding of both letters and digits with overlapping—although not identical—changes. This may be accounted for by two mechanisms with a developmental trajectory such as one stage of identification that is shared by both letters and digits along with an impact of letter-only processing. McCloskey and Schubert (2014) proposed that letter processing and digit processing are shared up to the level of abstract character identities, which is potentially consistent with changes in position coding for both types of characters. For example, the overall decrease in position errors in both types of characters may be due to developmental change at the level of stored forms or abstract identities. Position-specific changes within each character type may be due to influences of higher-level letter- and digit-specific processes such as lexical access (as in the lexical tuning hypothesis) and access to number semantics, respectively.

It has been suggested that certain familiar digit strings, such as the year of one's birth, are "lexicalized" (Leff & Starrfelt, 2014, p. 127), and naming of familiar digit strings has been preserved in some cases of poor naming of random digit strings (Beauvois & Dérouesné, 1979; Cohen, Dehaene, & Verstichel, 1994). A possible extension of the lexical tuning hypothesis could consider the influence of lexicalized digit strings by analogy to lexical entries composed of letters; this logic might predict some similarities in letter position processing and digit position processing. Future work should consider differences between familiar and unfamiliar digit strings in more detail to evaluate this line of theorizing.

No change in the precision of position coding was observed for symbols, consistent with a history of reported dissociation between letter/digit identification and non-alphanumeric processing for both children and adults. To our knowledge there are no explicit theories of typographical symbol recognition, but theories of general object recognition may serve this purpose. Unlike letters and digits, symbols of this type rarely occur in strings outside of contrived laboratory experiments, and so the demand to code their position precisely may be weaker (Collis et al., 2013).

Neural instantiation of letter and digit processing

Although it is beyond the scope of this article to review the neural bases of letter and digit processing in detail, we briefly note that recent neuroimaging findings may be relevant to the degree of overlap between letter identification and digit identification in both adults and children. Adult participants show a brain region that appears to be key to letter processing (the visual word form area or VWFA; e.g., Dehaene & Cohen, 2011) and show another that appears to be key to digit processing (the number form area or NFA; e.g., Grotheer, Herrmann, & Kovacs, 2016; Yeo, Wilkey, & Price, 2017). However, the neural specificity of these areas is still debated (e.g., Grotheer, Ambrus, & Kovács, 2016; Merkley, Wilkey, & Matejko, 2016), and the relevance of neural segregation for segregation at the cognitive level is unclear (McCloskey & Schubert, 2014; Schubert, 2017). Regardless of the outcome of these issues, the existence of reliably localizable letter and digit regions underscores the automaticity and expertise with which literate adults process these stimuli. Little work to date has considered the development of these areas (Cantlon, Pinel, Dehaene, & Pelphrey, 2011; Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015), and we hope that future work will consider the development of these areas in conjunction with behavioral study of these key reading skills.

Conclusions

In the wider theoretical context, there has been a growing consensus that letter and digit identification processes are shared in the adult system (Grainger & Hannagan, 2014; Kinoshita & Lagoutaris, 2010; Schubert, 2017). As discussed in the Introduction, a large body of evidence suggests that the serial position functions for letter strings and digit strings are highly similar (and different from symbol and shape strings) in adults. However, few studies and fewer theorists have considered the development of these identification systems and whether and how differences in the acquisition of proficiency with letter and digit identification could be explained within a shared system.

Our study is the most comprehensive investigation to date of children's identity and position processing of letters, digits, and symbols. Our results bear on two main theoretical issues in the literature: the development of visual expertise for letter/digit string identification (e.g., the MRF hypothesis) and the development of adult-like letter position coding (e.g., the MRM and lexical tuning hypotheses). We found only partial support for the MRF and lexical tuning hypotheses, leaving open a number of key questions. We hope that our results concerning changes in letter and digit identification accuracy over the primary school years will contribute to a larger base of evidence allowing further developmental theories of letter, digit, and symbol identity and position processing to be advanced and tested.

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Appendix

Accuracy by type and position by CC2 performance

All effects in the accuracy base model were preserved within letters, digits, and symbols. There was no effect of reading score on accuracy of letters, digits, or symbols (p = .07, p = .35, or p = .20, respectively). However, some interactions with reading score were revealed. The effect of reading performance differed between letters and symbols ($\beta = -0.52$, $SE = 0.19$, $z = -2.78$, $p = .005$), being larger for letters than for symbols. In symbols, reading ability was related to the size of the difference between the initial position and fixation ($\beta = 0.36$, $SE = 0.19$, $z = 2.56$, $p = .01$). Above-average readers showed higher accuracy on the initial position than did below-average readers ($ACC_{\text{below-average-readers}} = .20$, $ACC_{\text{above-average-readers}} = .31$), whereas performance at fixation improved only slightly ($ACC_{\text{below-average-readers}} = .25$, $ACC_{\text{above-average-readers}} = .26$). Similarly, performance at the second position also increased with higher reader ability ($ACC_{\text{below-average-readers}} = .18$, $ACC_{\text{above-average-readers}} = .26$) relative to fixation ($\beta = 0.52$, $SE = 0.19$, $z = 2.71$, $p = .007$).

Furthermore, the above-described effect, in which symbols show an effect of reading score on the difference between the second position and fixation, was not present in letters ($\beta = 0.79$, $SE = 0.27$, $z = 2.90$, $p = .004$) or in digits ($\beta = 0.55$, $SE = 0.27$, $z = 2.04$, $p = .04$).

In summary, reading performance was found to differ in its effect among letters, digits, and symbols. Letters showed a greater accuracy improvement than symbols as reading performance increased, whereas the symbol effect was specific to the initial and second positions in the string.

Position errors by type and position by CC2 performance

All effects in the position error base model were preserved within letters, digits, and symbols. There was no effect of CC2 score on the proportion of position errors in the letter, digit, or symbol conditions (all $ps > .25$). There was a three-way interaction among CC2 score, position, and character type ($\beta = -0.49$, $SE = 0.21$, $z = -2.37$, $p < .018$); in both letters and digits, as reading performance increased, the proportion of position errors at the second position and fixation both increased, but position errors at fixation increase more, and this increase was larger in the letter condition.

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