Skilled readers show different serial-position effects for letter versus non-letter target detection in mixed-material strings

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\textbf{ARTICLE INFO}

\textbf{Keywords:}
Literacy
Letter recognition
Analytic processing preference
Functional coordination
Skilled reading

\textbf{ABSTRACT}

The study explored whether target detection in a five-character string depends on whether a letter or a non-letter was presented, as a predesignated target. Skilled readers had to identify a single letter or non-letter in a five-character string, randomly composed of letters and non-letters. It was found that an analytic processing strategy is automatically elicited if participants were instructed to detect a letter target. In this instance, a linear model best explained the RT variance for letters: with increasing RTs from left to right, suggesting a serial item-by-item reading-specific strategy comparable to alphabetic reading. For non-letters, in contrast, a symmetrical U-shaped function best explained the RT variance, suggesting a symmetrical scanning-out from the central to the terminal positions of the string. Since the design precludes orthographic and semantic influences, it can be concluded that a reading-specific strategy for alphabetic processing is automatically activated if the string is scanned for a letter-target. Thus, the pre-designated target triggers the strategy for processing the string and determines related position effects. The results suggest that effects from earlier studies, which showed an analytic processing preference for isolated letters (APPLE) in recognition tasks, as a consequence of literacy acquisition, generalize to the processing of letters in strings.

1. Introduction

1.1. Analytic processing preference for letters

Reading text requires fast recognition of visual symbols, i.e., letters and words. No matter how important phonological processing skills are for reading (Snowling, 2001), the process always starts with a fast visual analysis. Processing strategies that are preferably used for fast visual object recognition include orientation-invariance, context sensitivity and other characteristics, which may be termed as “holistic processing”. Holistic processing, however, is not suitable for establishing a connection between letters with phonology, as a “b” is neither a “d” nor a “p” nor a “q” (Orton, 1925). Generally, a phoneme is represented by a very distinctive, orientation-specific visual symbol to be identified unambiguously within context. This requires analytic rather than holistic visual processing.\textsuperscript{1} Therefore, according to the Functional Coordination Approach (Lachmann, 2002, 2018; Lachmann & van Leeuwen, 2014), during the alphabetic phase of learning to read (Frith, 1985), in which grapheme-to-phoneme conversion rules are learned (i.e., letter knowledge), visual processing preferences must be modified for reading letters. This requires the suppression of holistic processing preferences in favor of an analytic strategy (Lachmann & van Leeuwen, 2014). In the following orthographic phase of reading acquisition, instead of letter-by-letter decoding, readers learn to recognize and pronounce units and whole words (Frith, 1985). Nevertheless, alphabetic letter-by-letter reading is still applied in skilled readers, if orthographic reading is less effective, e.g. for unknown regular words (Coltheart, 2007).

Both holistic and analytic processing strategies are, depending on task demand and stimuli, applied in visual perception (Wagemans et al., 2012).

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\textsuperscript{1} The analytic-holistic distinction is known under a variety of sometimes conflicting terminology, laden with theoretical baggage (Wagemans et al., 2012). In the present study it addresses a collection of empirical distinctions, depending on the extent: to which a perceptual configuration is perceived as independent of its context, to which the percept emphasizes properties of the parts over the whole, to which it is tolerant with respect to the constraints non-local properties impose on component organization, and to which it is oblivious to transformational invariants and/or symmetries. We speak of analytic when one of this applies, and of holistic if not.

\url{https://doi.org/10.1016/j.actpsy.2020.103025}

Received 8 July 2019; Received in revised form 11 December 2019; Accepted 3 February 2020

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Analytic processing is initially much slower and more demanding than holistic processing. When it is applied in the process of reading acquisition, it becomes fast and coordinated with other modified functions through extensive practice; thus forming a reading specific cognitive procedure, which is automatized as a package over years (Froyen, Bonte, van Atteveldt, & Blomert, 2009; Lachmann & van Leeuwen, 2008a, 2014; Nicolson & Fawcett, 2018). This will result in cross-modal codes of letters and words (Blomert, 2011).

The automatization of this reading specific procedure makes letters special for skilled readers, even outside the context of text. In particular, participants perceive letters faster and differently than similar non-letter shapes in recognition or classification tasks (Burgund, Schlaggar, & Petersen, 2006; Fernandes, Vale, Martins, Morais, & Kolinsky, 2014; Lachmann & van Leeuwen, 2008a,b). It was shown that the distinctive processing of letters is not simply the result of stimulus familiarity (Schmitt & van Leeuwen, 2017), but results from an automatized analytic processing preference for letters. This letter-specific processing effect was coined as the Analytic Processing Preference for Letters Effect (APPLE; Lachmann, 2018). For single letters, an APPLE was demonstrated in several studies that involved symmetry (Fernandes & Kolinsky, 2013; Lachmann & van Leeuwen, 2007; Pegado et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011; see also Duñabeitia, Dimitroutpolou, Estévez, & Carreiras, 2013), flankers (Fernandes et al., 2014; Lachmann & van Leeuwen, 2004, 2008a,b; van Leeuwen & Lachmann, 2004), and global preference (Lachmann, Schmitt, Braet, & Van Leeuwen, 2014; Schmitt & van Leeuwen, 2017). An APPLE was evident only in skilled readers, if alphabetic decoding was required or triggered by task and stimuli (Lachmann et al., 2014; van Leeuwen & Lachmann, 2004). Interestingly, skilled readers still do not automatically elicit this effect when trained to make new associations between non-letter configurations and phonology if the task can be solved in the absence of the association (Schmitt & van Leeuwen, 2017).

It remains unclear how analytic processing manifests in the context of reading text using the alphabetic route (Coltheart, 2007). In skilled readers, word reading is also driven by lexical information and semantic context, (orthographic route, see Coltheart, 2007; Rastle & Coltheart, 1999; see also Grainger & Ziegler, 2011, and Pegado & Grainger, 2019, and Mirault, Snell, & Grainger, 2019) which involves other than analytic visual processing strategies (Ventura, Fernandes, Leite, Pereira, & Wong, 2019). Therefore, in the present study design, these contents were excluded to explore the influence of analytic letter processing by investigating target detection within a character string; a task that mimics serial alphabetic reading. However, this does not imply that analytic letter processing is principally restricted to alphabetic reading or that alphabetic reading is exclusively based on a strict serial left-to-right analytic processing (see, e.g., Adelman, Marquis, & Sabatos-DeVito, 2010).

1.2. Position effects in searching strings

Haber and Standing (1969) demonstrated that when a letter is searched in a letter string, the central and terminal target positions were detected more accurately, than the neighboring positions, resulting in a W-shaped position function for accuracy (or a M-shaped for error rates). For reaction times, a similar pattern of results was found by Mason (1975). In five-letter strings, target letters were detected faster at the initial, central and final positions of the string (M-shaped position function) joined by an increase of reaction times from left to right (linear serial position effect). These results were explained by sensory mechanisms in that the left-to-right trend results from post-perceptual mnemonic organization (Harcum, 1967) and a response bias to the left side of the strings (Ayres, 1966), the central position advantage, as a consequence of foveal perception of the center letter, where visual acuity is greatest (Mason, 1982; Wagstaffe, Pitchford, & Ledgeway, 2005), and the terminal position advantage by lateral masking (Etes, 1972; Haber & Standing, 1969).

The pattern of results for letter detection differs from that found for non-letter targets detected in non-letter strings: there is still a preference for the central position, but no terminal advantage (Mason & Katz, 1976). To explore this difference, Hammond and Green (1982) systematically compared position effects for letter versus non-letter detection using a block design. Keeping all other conditions constant they found that the position effect for letters and non-letters differs in the appearance of the end-effect. For letter RTs, both the M-shaped function and the overall linear increase from left to right remained, whereas for non-letters a U-shaped function with a symmetrical increase in RTs from the central to the terminal positions was observed. The authors found that this distinction is not due to factors such as visual complexity, familiarity or the ability to name it. Moreover, Mason (1982) showed that the distinction in processing between letter and non-letter detection was independent from retinal placement (foveal vs. parfoveal) and array size (three- vs. five-character string). These results suggest that the position functions cannot simply be explained by sensory mechanisms but require cognitive processes. This view is supported by the fact that the position functions for letters are highly sensitive to linguistic factors, such as orthographic, morphological and lexical constraints (Farid & Grainger, 1996; Ktori & Pitchford, 2008, 2009; Mason, 1975; Pitchford, Ledgeway, & Masterson, 2008).

Mason (1975) demonstrated that the speed of letter detection also correlates with spatial frequency redundancy, i.e., how frequently a specific letter is at a specific position in written real words (e.g., “y” is highly frequent at the end of English printed words) and with sequential redundancy, i.e., sequential order of specific letters in typical multi-letter units (e.g., the letter “h” often proceeds the letter “y”). Likewise, the overall left-to-right increase depends on participants’ typical reading habits. Consequently, whereas this trend was observed for French readers, it vanished entirely for Arabic readers (Farid & Grainger, 1996). This was due to the difference in morphological systems of the French and Arabic languages. In contrast, Greek readers exhibit a distinctive left-to-right trend along with a lack of the advantage of the last position, as a result of the strict orthographic transparency of the written language (Ktori & Pitchford, 2008, 2009).

Tydtag and Grainger (2009) examined whether the letter vs. non-letter distinction also holds for mixed strings in which a target or non-target letter was presented in a string of non-letter symbols, or vice versa. The results suggest that for mixed strings, depending on whether the target was a letter or a non-letter, the typical letter or non-letter position functions appeared respectively. Driven by this result, Grainger, Tydtag, and Isselé (2010) yielded an alternative approach, which integrated the sensory mechanisms and cognitive processes in the context of crowding. They predicted a distinction of crowding space between letters and non-letters. To test this hypothesis, they presented letters or non-letter symbols peripherally, flanked by either one or two items of the same category. The flanker interference was significantly larger for non-letter symbols compared to letters. By varying the space between target and flankers, they demonstrated that also the critical space, in which flankers interfere with the target, was larger for non-letter symbols than for letters. Hence, Grainger et al. (2010) proposed that there is a specialized system, developed during reading acquisition, which determines crowding space. Note, since in their paradigm the target letters respectively symbols succeeded the string, memory effects cannot be excluded.

According to Stevens and Grainger (2003), the reduction of the receptive field for letters is a result of reading acquisition to enable parallel processing of letters in words. Lateral masking can explain the facilitation of terminal positions in letter strings, but not the disappearance of this effect in non-letter strings, whereas the crowding hypothesis can explain both. For non-letters even a single flanker interferes with the target. The shrunked receptive field for letters leads to a decrease of interference and thereby, to a facilitation of the terminal positions, where letters are only flanked by one distractor compared to the inner positions where they are flanked by at least two distractors.
Note, that the assumption of different crowding areas can explain the end-effects, but neither the linear trend nor the letter-frequency effects. However, the idea that letters are processed in a restricted area also fits the assumption of an analytic letter-specific processing strategy (Lachmann & van Leeuwen, 2014), which is biased to the internal features of letters, as predicted by the APPLE (Lachmann, 2018).

1.3. The target determines the journey

The studies described thus far showed that the processing of letter strings differs from the processing of non-letter strings. This suggests that the predicted, letter-specific processing strategies, such as the APPLE, may not be restricted to isolated letters but also influence the perception of letters in strings, and thus, may be generalized to alphabetic reading.

For non-letter strings, if the stimuli were presented centrally, the pattern of responses creates a quadratic U-shaped function of reaction times and error rates, explained by sensory mechanisms involving a center-out scanning (Hammond & Green, 1982; Pitchford et al., 2008). The quadratic term of the functions describes the decrease of visual acuity from the foveal to the parafoveal retinal field (Wagstaffe et al., 2005).

For letter strings, this sensory explanation only holds for an advantage at the central position. The facilitated end-effects, as well as, the linear left-to-right trend can only be explained by cognitive processes, as a result of an acquired and automatized letter-specific processing strategy and related reading habits (Grainger et al., 2010; Stevens & Grainger, 2003), e.g. the serial decoding of letters in written words (Green, Hammond, & Supramaniam, 1983; Hammond & Green, 1982; Ktori & Pitchford, 2008, 2009) during alphabetic reading (Coltheart, 2007; Frith, 1985, 1986). Hence, the serial position functions for letters depend on length and crowding of the string (Grainger et al., 2010), the fixation position (Tydgat & Grainger, 2009) and the eccentricity from the focal point of view (Chanceaux & Grainger, 2012), the frequency of specific letters in written real words (Mason, 1975; Pitchford et al., 2008) and reading ability (Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). It should be noted that depending on language-specific morphological and orthographical constraints, only the advantage for the initial and central position could be observed (Farid & Grainger, 1996; Ktori & Pitchford, 2008, 2009).

The typical finding with letter strings, i.e. the left-to-right trend and the terminal position advantage, can be interpreted as an automatized reading-specific strategy via the alphabetic route, including fast analytical visual processing. It was shown, that this strategy is not elicited by intentional choice, but runs automatically if alphabetic processing is required or triggered by the task (Lachmann, 2018; Lachmann & van Leeuwen, 2004). Hence, the distinctive processing for letters vs. non-letters may not be caused by the kind of characters in the string, but by the kind of the target to be identified, i.e., a letter or a non-letter. In other words, if the target is a letter then a cross-modal code is activated, which triggers a letter-specific strategy in the search of the string, regardless of any non-letter components that may be within it. In that case, we expect to observe evidence for an analytical strategy also in mixed character strings, i.e. strings, randomly composed of letters and non-letters.

In the target-detection task of the present study, participants had to decide whether a pre-designated target, either a letter or a non-letter, is part of a five-character string. The strings randomly include both letters as well as non-letters. Note, that these character-strings were used in both conditions, i.e., when a letter as well as when a non-letter had to be detected and that the target precedes the character string. Therefore, we can exclude that potentially different position effects for letter versus non-letter detection are due the composition of the string but can only be explained by different processing strategies depending on whether the target is a letter or a non-letter. It is predicted that letter targets elicit analytic processing when searching in the string. In accordance to former results, it is predicted that this reading-specific analytic processing would produce a linear left-to-right increase for target detection RTs, as well as, a terminal position advantage, at least, at the initial position. In contrast, we expect that this analytic processing is not elicited by non-letter targets notwithstanding if the same strings have to searched. This would result in a symmetric center-out scanning with larger detection times for the terminal than for the inner positions.

2. Method

2.1. Participants

Forty-one students from the University of Kaiserslautern, Germany (between 19 and 29 years old; 24 male), were either paid or received course credit for their participation. All participants were right handed, German native speakers with normal or corrected to normal vision, were fluent readers of German text and were unfamiliar with the Hebrew or the Cyrillic script. Participants gave written consent for participation in this study. The study was approved by the ethical committee of the Faculty of Social Sciences of the University of Kaiserslautern in accordance with the Declaration of Helsinki (World Medical Association, 2008).

2.2. Material and apparatus

Stimuli were four letters from the Latin script, four Cyril letters and four Hebrew letters (see Fig. 1, left side). They were designed in such a manner that visual features (lines, curves, number of elements, angles, closure etc.) and complexity (Information Load measure, see Buffart & Leeuwenberg, 1983) between the three script categories are matched. Skilled readers of Latin, Hebrew and Cyrillic script were consulted about these designs and confirmed that they are representative of graphemes that exist within their respective languages. The participants considered the Latin letters to be “letters” of a familiar script, while Cyrillic and Hebrew letters were unfamiliar to them and were thus considered to be “non-letters”. The stimuli were presented as targets to be detected in strings, which were combinations of five different stimuli randomly chosen from the possible twelve, regardless if these were Latin letters, Hebrew letters or Cyrillic letters (for an example see Fig. 1, right side). The stimuli were presented in black (0.4 cd/m²) against a white background (28.9 cd/m²). Individual stimuli were presented with a visual angle of approximately 0.5° × 0.5°, the strings with a total visual angle of approximately 3° in width.

Fig. 1. Illustration of the stimuli designed for this study. Character strings (right) were randomly composed of five different characters from the three letter groups (Latin letter, Cyrillic letters and Hebrew letters; left). Complexity and similarly was controlled to make stimuli comparable between categories (first column contains only letters with diagonals, the second only letters with orthogonal angles, the third column only letters with a half circle, and the fourth column only letters with a zig-zag structure).
The experiment was run on a PC with Windows 7 using E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA) and took place in a Deson® test cubicule with sound attenuation and controlled lighting. There was no fixation of the head.

2.3. Procedure

The experiment was a target-detection task, which consisted of 480 trials spread over two sessions. The task was performed in one day with a 5 min break between the sessions. Participants had to decide whether or not a pre-designated target (either a Latin, or a Cyrillic, or a Hebrew letter), was part of the presented character string. Participants were instructed to respond as quickly and as accurately as possible by pressing either the “s” or the “l” button on the keyboard. They were instructed to press “s” with their left index finger if the target character was part of the string or “l” with their right index finger if not was. The assignment of keys and response alternatives was counterbalanced between participants. From the set of 95,040 theoretically possible character strings, the presented combinations were counterbalanced in the following way: Each character appeared 40 times as target. In half of the trials, the target was absent, i.e., the target was not part of the character-string. The remaining 20 trials were counterbalanced in a way that the target was present for four times on each possible position of the five-character string. In sum, each kind of letters (Latin, Hebrew, Cyrillic) was shown 16 times on each position.

Each trial began with the presentation of the target character in the center of the screen for 1000 ms, followed by a blank screen for 500 ms. The stimuli were shown centrally, until the participants responded. After a blank screen, shown for 1500 ms, the next trial began. Participants completed 30 training trials, in which visual feedback on their individual reaction times and accuracy was presented for 1000 ms.

3. Results

Two participants were excluded from further analysis, because of an accuracy was <70%. Assuming an effect size of 0.3 for the remaining 39 participants a statistical power of 0.95 was calculated using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Error rates (ER) and mean reaction times (RT) of correct responses within a range of 150 ms and 2000 ms (95 trials were excluded, 0.5%) were analyzed. The overall mean ER was 11.5% (SD = 6.9%) and ranged from 0.2% to 28.2%. The overall mean RT was 633 ms (SD = 127 ms) and ranged from 414 ms to 1038 ms. Since there was a speed-accuracy trade off, the second position for letter strings, the presented combinations were counterbalanced in the following way: Each character appeared 40 times as target. In half of the trials, the target was absent, i.e., the target was not part of the character-string. The remaining 20 trials were counterbalanced in a way that the target was present for four times on each possible position of the five-character string. In sum, each kind of letters (Latin, Hebrew, Cyrillic) was shown 16 times on each position.

Each trial began with the presentation of the target character in the center of the screen for 1000 ms, followed by a blank screen for 500 ms. The stimuli were shown centrally, until the participants responded. After a blank screen, shown for 1500 ms, the next trial began. Participants completed 30 training trials, in which visual feedback on their individual reaction times and accuracy was presented for 1000 ms.

### 3.1. RT analysis

We observed main effects for Material, F(2, 76) = 36.77, p < .001, η² = 0.49, BF₁₀ > 100 and for Position, F(4, 152) = 33.46, p < .001, η² = 0.47, BF₁₀ > 100, as well as a Material × Position interaction, F(8, 304) = 8.11, p < .001, η² = 0.18, BF₁₀ > 100. To explore this interaction, we compared materials (Latin, Hebrew, Cyrillic) pairwise in post-hoc ANOVAs. Results are summarized in Table 1.

As shown in Table 1, the post-hoc ANOVA for Hebrew versus Cyrillic showed neither a main effect for Material nor an interaction between Position and Material, whereas the ANOVA for Latin versus Hebrew and Latin versus Cyrillic showed both, a main effect for Material and a Material × Position interaction. Since there were no differences between Hebrew letters and Cyrillic letters and our participants were not at all familiar with either the Hebrew or the Cyrillic script, these two factor levels were merged to one factor level in all further analyses. Thus, for RTs, in the following we will have the factor Material with the two sample-specific levels letters (Latin letters, known to all of our participants) versus non-letters (Cyrillic and Hebrew letters, both unknown to our participants).

Considering this new factor level, the 2 (letters vs. non-letters) × 5 (positions 1–5) ANOVA showed the following results: Once more, there were main effects for Material, F(1, 38) = 44.37, p < .001, η² = 0.53, BF₁₀ > 100, with faster responses for letters (575 ms) than for non-letters (632 ms) and Position, F(4, 152) = 28.03, p < .001, η² = 0.42, BF₁₀ > 100, showing that responses are faster for the center position (Position 3, 564 ms) and become slower the further they move away from the central position (Position 2: 590 ms, Position 4: 608 ms, Position 1: 611 ms and Position 5: 642 ms). Also the Material × Position interaction, F(4, 152) = 15.31, p < .001, η² = 0.29, B > 100, was still observed.

In order to explore this interaction, we conducted 2 × 2 ANOVAs, with the factors Material (letters vs. shapes) and Position, with pairwise comparison for the positions within the string (e.g., Position 1 vs. Position 2, Position 1 vs. Position 3, etc.). Since we were especially interested in the effects of the string onset (i.e., Material × Position interaction for Position 1 and 2), the string core (i.e., Material × Position interaction for Position 2 and 3, respectively 3 and 4) and the string end (i.e., Material × Position interaction for Position 4 and 5), we here only report the relevant effects and the related results of post-hoc Bonferroni corrected t-tests (results of the complete analyses of interactions are given in Table A of the Appendix).

For the string onset (Position 1 vs. 2), there was a Material × Position interaction, F(1, 38) = 55.30, p < .001, η² = 0.59, BF₁₀ > 100, with faster reactions for the first compared to the second position for letter strings, t(38) = 3.04, p = .004, BF₁₀ = 8.58, but slower reactions for the first compared to the second position for non-letter strings, t(38) = 6.44, p < .001, BF₁₀ > 100.

There were main effects for string core for Position (Position 2 vs. 3, F(1, 38) = 20.93, p < .001, η² = 0.36, BF₁₀ = 72.28; Position 3 vs. 4, F(1, 38) = 58.96, p < .001, η² = 0.60, BF₁₀ > 100), indicating central position advantages for letters (Position 2 vs. 3, t(38) = 3.48, p < .01, BF₁₀ = 24.82; Position 3 vs. 4, t(38) = 4.10, p < .001, BF₁₀ > 100) and non-letters (Position 2 vs. 3, t(38) = 3.19, η² = 0.05, BF = 0.13).

| Table 1 Results of post-hoc ANOVAs of mean RTs pairwise for letter groups. |
|-----------------|-----------------|-----------------|
| Material        | Latin vs. Hebrew| Latin vs. Cyrillic|
| Material        | F(1, 38) = 67.94, p = .110, η² = 0.07, BF = 0.22 | F(1, 38) = 43.53, p < .001, η² = 0.53, BF > 100 |
| Position        | F(4, 152) = 36.69, p < .001, η² = 0.49, BF > 100 | F(4, 152) = 19.33, p < .001, η² = 0.34, BF > 100 |
| Material × Position | F(4, 152) = 1.84, p = .125, η² = 0.05, BF = 0.13 | F(4, 152) = 8.64, p < .001, η² = 0.19, BF = 60.29 |
| Material        | F(1, 38) = 38.72, p < .001, η² = 0.50, BF > 100 | F(4, 152) = 26.84, p < .001, η² = 0.41, BF > 100 |
| Position        | F(4, 152) = 26.84, p < .001, η² = 0.50, BF > 100 | F(4, 152) = 26.84, p < .001, η² = 0.41, BF > 100 |
| Material × Position | F(4, 152) = 14.11, p < .001, η² = 0.27, BF > 100 | F(4, 152) = 14.11, p < .001, η² = 0.27, BF > 100 |
BF₁₀ = 12.24, p > .01; Position 3 vs. 4, t(38) = 6.35, p > .001, BF₁₀ > 100). There was no Material × Position interaction for Position 2 vs. 3, F(1, 38) = 1.21, p = .27, η_p² = 0.03, BF₁₀ = 0.36, neither for Position 3 vs. 4, F(1, 38) = 0.53, p = .47, η_p² = 0.01, BF₁₀ = 0.28.

For the string end (Position 4 vs. 5), a main effect for Position, F(1, 38) = 26.37, p < .001, η_p² = 0.41, BF₁₀ = 64.64, shows larger RTs for the last compared to the fourth position for letters, t(38) = 2.40, p < .05, BF₁₀ = 2.17, as well as for non-letters, t(38) = 5.43, p < .001, BF₁₀ > 100.

Tendencies of RTs across the positions in the strings are displayed in Fig. 2. For non-letters, the mean RTs described a U-shape with slow responses for the first position (664 ms), fastest responses for the central position (Position 3: 582 ms) and again slow responses for the last position (Position 5: 679 ms). For letters, there was no such U-shaped function, resulting from fast RTs at the first position (557 ms), which did not differ significantly from RTs at the central position (Position 3: 546 ms). For letters, in contrast, slowest responses were observed at the right terminal position (Position 5: 610 ms) of the string, too.

To examine the best fitting serial position function, we performed a trend analysis. Considering all positions for letters, results showed a significant linear effect, F(1, 38) = 13.14, p < .001, as well as a quadratic effect, F(1, 38) = 138.91, p < .001, explaining 91.7% of variance. For non-letters, there was still a linear effect, F(1, 38) = 6.9, p < .05, as well as a quadratic effect, F(1, 77) = 71.17, p < .001, which explains 91.7% of variance.

The resulting serial position functions are as follows:

- For letters: RT(L) = 564.2 - 11.3 * (pos - 3) + 5.6 * (pos - 3)²
- For shapes: RT(S) = 590.4 - 5.9 * (pos - 3) + 20.4 * (pos - 3)²

Results showed a significant linear effect, F(1, 38) = 13.14, p < .001, for letters, explaining 88.2% of variance. An expanded model, including an additional squared term did not show a significant improvement, χ²_diff (1) = 0.07, p = .8, showing that after excluding the advantage caused by fixation, RTs in letter strings only show a linear serial position effect.

For non-letters, there was still a linear effect, F(1, 38) = 6.9, p < .05, as well as a quadratic effect, F(1, 77) = 71.17, p < .001, which explains 91.7% of variance.

3.2. Error rate analysis

Analysis of arcsin square-root transformed ERs showed similar results to that of mean RTs. Mean ERs for different positions and material are illustrated in Fig. 3. Main effects were observed for Material, F(2, 76) = 21.97, p < .001, η_p² = 0.36, BF₁₀ > 100, and for Position, F(4, 152) = 8.68, p < .001, η_p² = 0.19, BF₁₀ > 100, and a Material × Position interaction, F(8, 304) = 3.74, p < .001, η_p² = 0.10, BF₁₀ = 5.03. Post-hoc ANOVAs, comparing the letter groups pairwise, showed Material × Position interactions for Latin vs. Hebrew, F(4, 152) = 3.20, p < .05, η_p² = 0.08, and for Latin vs. Cyrillic, F(4, 152) = 7.34, p < .001, η_p² = 0.16. As for RTs, for ER there was no interaction between Hebrew vs. Cyrillic either, F(4, 152) = 1.34, p = .26, η_p² = 0.03, BF₁₀ = 0.09. Therefore, these factor levels were merged into the factor level, non-letters, in further ER analyses. Equally to our RT analyses, now there are two sample-specific levels of the factor Material, letters (Latin letters, know to all of our participants) and non-letters (Cyrillic and Hebrew letters, all unknowns to our participants).

The 2 (letter vs. non-letters) × 5 (position 1–5) ANOVA, showed a similar pattern of results as the RT analyses. There were main effects for Material, F(1, 38) = 55.78, p < .001, η_p² = 59, BF₁₀ > 100, with less errors for letters (8.7%) than for shapes (14.2%), and Position, F(4,
Results from pairwise t-tests of ERs for positions in the non-letter strings. Table 2

Fig. 3. Mean ER for positions in letters (left) and shapes (right). The line illustrates the best fitting function (ER(L) and ER(NL)).

152) = 5.57, \( p < .001 \), \( \eta^2 = 0.13 \), BF\(_{10} = 75.54 \), showing a low ER for the center position (Position 3: 92.7%), and increasing ER for positions that are further away from the central position (Position 2: 10.7%, Position 4: 11.4%, Position 1: 14.9% and Position 5: 13.0%). Also the \text{Material} \times \text{Position} interaction, \( F(4, 152) = 6.01, p < .001 \), \( \eta^2 = 0.14 \), BF\(_{10} = 11.53 \), was still observed. Due to this interaction, letters and non-letters were analyzed separately.

For letters, ERs did not differ significantly for Position, \( F(4, 152) = 1.87, p = .118 \), \( \eta^2 = 0.05 \), BF\(_{10} = 0.27 \), although the mean ER at the fixation point (Position 3: 5.3%) was slightly lower compared to the mean ERs at the other positions (Position 1: 8.4%, Position 2: 9.5%, Position 4: 10.4%, Position 5: 9.9%). For non-letters, there was an effect for Position, \( F(4, 152) = 12.32, p < .001 \), \( \eta^2 = 0.24 \), BF\(_{10} > 100 \), and thus, the differences of mean ERs for positions in the non-letter-string were compared in pairwise Bonferroni corrected t-tests (see Table 2).

As shown in Table 2, the mean ER at Position 1 (21.3%) was significantly higher compared to all other positions and additionally the mean ER at Position 5 (16.1%) was significantly higher compared to the center position (Position 3: 9.3%). Although results of the remaining positions (Position 2: 11.8%, Position 4: 12.5%) did not differ significantly from the central position, trend analyses were performed, to test whether a U-shape function provides the best fitting of mean ERs for non-letters.

The best serial position function for non-letters, \( ER(\text{NL}) = 9.5 + 2.3 \times (\text{pos} - 3)^2 \) shows a significant quadratic effect, \( F(1, 38) = 49.78, p < .001 \), and explains 54.1% of the variance. An expanded model including an additional linear term did not show a significant improvement, \( \chi^2_{\text{adj}}(1) = 3.08, p = .08 \).

For letters, the best serial position function, \( ER(\text{L}) = 8.7 + 0.4 \times (\text{pos} - 3) \) showed a slight but not significant linear effect. However, the linear model shows a significant improvement, compared to a baseline model, which only assumes random intercepts caused by participants, \( \chi^2_{\text{adj}}(1) = 10.89, p < .05 \).

4. Discussion

In this study, we compared processing strategies in a target detection task, depending on whether a letter or a non-letter was presented as a target to be identified in a five-character mixed-material (letters and non-letters) string. Prior studies demonstrated that if a letter target has to be detected in a letter string, processing is more analytical, i.e. the string is processed item-by-item from left to right with a benefit for the terminal positions. In contrast, strings composed of non-letters are processed in a more holistic manner when scanned for a non-letter target, i.e. symmetrical scanning-out from the central to the terminal positions of the string.

By using strings randomly composed of Latin letters, Hebrew letters and Cyrillic letters, we determined whether these different processing strategies are triggered by the string or by the target, when either a letter (Latin) or a sample-specific non-letter (Hebrew letter/Cyril letter) had to be detected. We expected that effects from earlier studies (see Lachmann, 2018; or Lachmann & van Leeuwen, 2014, for a review), which showed an analytic processing preference for letters and a holistic processing preference for non-letter items in recognition tasks, generalize to the processing of letters and non-letters in strings. The hypothesis was that the analytic processing strategy would be automatically elicited, if participants are instructed to detect a letter target; resulting in increasing RTs from the left end of the string, to the right.
end. Since the participants were not familiar with reading Hebrew or Cyrillic (sample-specific non-letters), our expectation was that this reading-specific strategy would not be elicited when they are instructed to detect items from these alphabets. Consequently, instead of a linear increase from left to right, a symmetrical increase in RTs was expected for sample-specific non-letters, with fastest responses for the central position and slowest responses for the initial and final positions.

The present results support this hypothesis. For RTs, a linear model best explained the variance for Latin letters while for sample-specific non-letters, a symmetrical U-shaped function best explained the variance in RT. A similar distinction in position effects was found for ERs. An advantage for letters for the final position was not observed as would be expected for readers which are trained in reading German written language following strict transparent orthographic rules (Kitori & Pitchford, 2008, 2009). Since the present design precludes orthographic and semantic influences, it can be concluded that a reading-specific strategy for alphabetic processing is automatically activated if the string is searched for a letter-target. Since in both target conditions (letter and non-letter), the strings were randomly composed of both letters and non-letters, the pattern of results could only be attributable to the target material. Thus, the pre-designated target triggers the strategy for processing the string and determines related position effects. A letter-target automatically activates a cross-modal representation (i.e., merged graphemic and phonological information), and accordingly analytic processing, akin to strict alphabetic reading (e.g. for non-words or unknown regular words, in which a correct pronunciation requires a serial letter-by-letter decoding), for searching the string item-by-item from left to right.

However, if the target is a non-letter, why is the proposed reading-specific processing strategy for letters not activated by letters in the string? In earlier studies, it was shown that a reading-specific analytic strategy in letter recognition was not elicited by intentional choice, but runs automatically if (a) participants were skilled readers (Duñabeitia et al., 2013; Fernandez et al., 2014; Lachmann, Khera, Srinivasaan, & van Leeuwen, 2012; Lachmann & van Leeuwen, 2008a; Schmitt, Lachmann, & van Leeuwen, 2019), (b) presentation conditions are similar to those of normal reading (e.g. visual angle; Lachmann et al., 2014; presentation times, Lachmann & van Leeuwen, 2008b) and (c) the task triggers alphabetic processing (van Leeuwen & Lachmann, 2004). For example, in tasks using contextual embedded stimuli (e.g., targets surrounded by irrelevant non-targets; Fernandez et al., 2014; Lachmann & van Leeuwen, 2004), different effects for letters and non-letters were found if skilled readers were instructed to make a categorical decision for which alphabetic processing was required (letter vs. non-letter). Then, letters were processed analytically (suppression of irrelevant flankers), while non-letters were processed holistically (integration of irrelevant context). In contrast, participants processed these embedded letters and non-letters in the same holistic manner if it was possible to make a decision on the basis of visual similarity (i.e., visually similar letters and non-letters belong to the one response category, Lachmann & van Leeuwen, 2004) while alphabetic processing was less beneficial (e.g., letters and non-letters belong to one response category; van Leeuwen & Lachmann, 2004). This means that a connection between visual and phonological information is necessary but not sufficient to elicit an analytic processing strategy.

Since in the present study (a) the participants were skilled readers, (b) the visual angle for the single items and the strings mimic those for reading letters and words (Jordan & Martin, 1987; Legge, Pelli, Rubin, & Schleske, 1985), and (c) the task triggers alphabetic processing, we can conclude that if the target is a letter, a cross-modal code and an analytic processing strategy is automatically activated for searching the string. This occurs regardless of whether any non-letter components may appear within the string. If the target is a non-letter, this strategy is not elicited, regardless of any letter components in the string. A question that may be raised is what would be the case if the target, either a letter or a non-letter, is presented after the mixed string i.e. would seeing a letter in the string activate an analytic strategy for processing the following target?

The present study suggests that a letter-specific analytic processing preference (APPLE), evident in previous single letter recognition studies, can be generalized to the processing of letters in strings. It could be critically argued that this distinctive processing strategy for letters does not necessarily arise from automatized reading skills, the connection with phonology and the presentation mode. For instance, the distinction found in the search strategy could result from the difference in the “nature of the stimulus” (Poirel, Pineau, & Mellet, 2008), in particular the higher familiarity and the meaningfulness of letters. An earlier study (Schmitt & van Leeuwen, 2017) showed, however, that even extensive training (familiarity) of learned associations between non-letters and phonology (meaning) does not lead to an analytic processing of these non-letter items if the task can be solved without alphabetic decoding.

Another argument could arise from the finding that letters in a very briefly presented short word are processed simultaneously and not in a left-to-right sequence (Rumelhart & McClelland, 1982; Tydgat & Grainger, 2009), if this word has to be selected from two options that participants thought they had just seen (Adelman et al., 2010). Early letter identification involved in word recognition were also identified in a number of other studies (Marzouki & Grainger, 2014; Scaltritti, Dufau, & Grainger, 2018; Stevens & Grainger, 2003; Tydgat & Grainger, 2009), in which participants (even children, Ziegler et al., 2010) had to identify a probed character at a specific location in a briefly presented letter string. These results demonstrate the flexibility of the visual system as a function of time course. The tasks in these studies, however, do not require alphabetic reading, which is the strategy automatized in the alphabetic phase of literacy acquisition and applied by skilled readers if other strategies are less efficient.

A further critique could be that in the present study the presentation time of the target and the time between target and string was relatively long compared to other studies (e.g., Ziegler et al., 2010), while it was found in Lachmann and van Leeuwen (2008b) that occurrence of the APPLE depends on this Stimulus-Onset-Asynchrony (SOA). In the latter study, however, the distinction between letter and non-letter processing vanished only when SOA was considerably longer than in the present study.

Another possible critique concerns the design of the mixed material strings. The items were randomized, which means that one string could include from zero up to four letters in different positions. Thus, if the target is a letter, these potential non-target letters in the string adopt a role of distractors. Therefore, the results for the target letter could additionally depend on the distribution of letters and non-letters in the string. Considering the left-to-right reading strategy, the distraction would be stronger if there are letters on the left side compared to the right side of the target position. In the same manner, the appearance of random consonant-vowel (CV) structures could benefit grouping effects (Bock, Monk, & Hulme, 1993), influencing letter detection in the strings; moreover, if the letter combinations match meaningful abbreviations (Rack, Hulme, Snowling, & Wightman, 1994), e.g. “AEG” for one of the biggest electronic companies in Germany. In the present study, however, only approximately 14% of all random strings included more than two letters, and only about 11% of all strings included CV structures. Since these values are equally spread over all positions, neither an influence of letter vs. non-letter distribution nor grouping effects for CV structures can be inferred on the basis of the collected data. Consequently, based on the aforementioned, these effects appear to be negligible on the results of the present study. It seems worth, however, to investigate the influence of the architecture of the string systematically in future research. Taken altogether, the present results support the assumption of a letter-specific processing strategy as the consequence of reading acquisition and extend them to context.
References


