Positional cueing, string location variability, and letter-in-string identification

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Short title: Cueing letter-in-string identification

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Abstract

In three experiments we measured accuracy in identifying a single letter among a string of five briefly presented consonants followed by a post-mask. The position of the to-be-identified letter was either indicated by an ordinal cue (e.g., position 2) or an underscore cue (e.g., #####). In Experiment 1 the ordinal cue was presented prior to onset of the letter string, and the underscore cue presented at string offset. In Experiments 2 and 3, both the ordinal and the underscore cues were pre-cues. In all experiments, letter strings could either appear centered on fixation or shifted randomly to the left or to the right. Participants were tested in separate blocks of trials for each of the four conditions generated by the combination of cue-type and string-location variability. In Experiment 1, letter identification accuracy was higher with ordinal cues and with fixed string locations, and ordinal cueing was more affected by string location variability. In Experiments 2 and 3, letter identification accuracy was higher with underscore pre-cues. We conclude that under conditions of brief stimulus durations (100 ms) and backward masking, letter-in-string identification accuracy is determined by read-out from location-specific letter detectors, independently of the type of cueing. Differences in the effectiveness of different types of cue are determined by differences in the ease of isolating a given gaze-centered location, and by differences in the ease with which attention can be directed to that location.

Key words: Letter identification; Orthographic processing; Positional cueing; Spatial attention

INTRODUCTION

In the present study we investigated the impact of the nature of the cue used to indicate which letter to report on performance in identifying a single letter among a string of five briefly presented and backward-masked letters. We specifically focus on cueing effects on letter-in-string identification given the evidence that readers develop a specialized mechanism for parallel letter processing (e.g., Chanceaux & Grainger, 2012; Chanceaux et al., 2013; Tydgat & Grainger, 2009). The key studies here used random consonant strings in order to minimize contributions from higher-level phonological, morphological, or lexical representations. A typical trial in such studies involves a central fixation point followed by a briefly presented string of randomly selected consonants (e.g., PFMLD), immediately followed by a post-mask that is accompanied by a cue indicating the position at which a single letter has to be identified (see Tydgat & Grainger, 2009, for a review of earlier studies).

The focus of prior research was on the form of the serial position function for letter-in-string identification, with most studies revealing highest accuracy at the first, last, and central (on fixation) positions (see Grainger et al., 2016, for a review and explanation). One key finding reported by Tydgat and Grainger (2009) is that the form of the serial position function is quite similar for letters and digits, both of which differ from strings of symbols or simple shapes (see also, Chanceaux & Grainger, 2012). This led to the hypothesis that performance in the letter-in-string identification task is based on activity in location-specific letter identities. That is, letter identities associated with a gaze-centered location along a line of text (e.g., the letter T located 3 letter spaces to the left of eye fixation location). This would involve a specialized mechanism developed during learning to read, and a similar mechanism would be applied to initially process numbers (i.e., a bank of horizontally aligned digit detectors; see Grainger & Hannagan, 2014, for a review of the evidence). In the present work we will largely ignore the shape of serial position functions (although these data have been made available) in order to focus on the impact of two factors that have received little attention in the past: the type of cue used to indicate which letter to report; and the degree of variability of the location of the string in which the target letter appeared.

The theoretical backbone guiding the present work is the first level of orthographic processing in the Grainger and van Heuven (2004) model. In this model, orthographic processing commences with the parallel association of letter identities to location-specific, gaze-centered locations (see also Dehaene et al., 2005, for a similar approach). In most alternative accounts of orthographic processing, orthographic processing begins with the association of location-invariant letter identities to their positions in a string of letters (e.g., Gomez et al., 2008). That is, when presented with the letter string TGPFM, rather than associating the letter T to a given gaze-centered location independently of its position in the string (e.g., the letter T located 2 letter spaces to the left of eye fixation location), as in the Grainger and van Heuven model, the letter T is associated with the first position in a string of 5 letters (with position of the letter and the length of the string more or less precisely defined depending on the model). This type of processing occurs at the second, location-invariant, level in the Grainger and van Heuven model. This processing delivers a representation of letter order that is crucial for word identification, and we will henceforth refer to this as an ordinal code.

The first manipulation of the present study involved the nature of the cue provided to participants in order to indicate which letter they had to identify among a string of five random consonant strings. We began by comparing a positional pre-cueing procedure, where participants were asked to report the letter at a given position in the target string of letters (an ordinal cue: e.g., "identify the letter at the 2nd position"), with the traditional location post-cueing procedure where target location is indicated at stimulus offset by an underscore (or other form of physical indication of location). In both cueing conditions the string of letters was presented for 100 ms and immediately followed by a pattern mask. We immediately acknowledge that cue type (ordinal vs. underscore) is confounded with cue timing (pre- vs. post-cue) in this manipulation,[1] but this was maintained in order to compare the traditional underscore post-cue with a positional (ordinal) cue. Given that an ordinal cue clearly requires additional processing compared with an underscore cue, this would have left more time for memory decay when applied as a post-cue, hence the pre-cueing with the ordinal cue. The hypothesis behind this manipulation, couched in the framework of the Grainger and van Heuven (2004) model of orthographic processing, is that ordinal cueing should primarily tap a location-invariant level of processing and hence be less sensitive to changes in target string location than the underscore cue, which is hypothesized to primarily tap a location-specific level of processing. Hence the second manipulation in the present study involved shifting the string location on some trials. More precisely, the string of 5 consonants could either appear at the same central location in one block of trials, or randomly at the center or shifted to the left or to the right in a separate block of trials. Experiment 1 also involved a between-participant (Experiment 1A & Experiment 1B) manipulation of the degree of displacement in the variable string location condition.

In sum, under the hypothesis that performance in a letter-in-string identification task with briefly presented and backward-masked random consonant strings is based on read-out from gaze-centered location-specific letter detectors, we predicted that location (underscore) cues should lead to higher accuracy than position (ordinal) cues. We further predicted that string location variability should have a bigger negative impact with ordinal cues than underscore cues. More generally speaking, we expected the manipulation of cue-type and string variability to shed light on the mechanisms involved in identifying a single target letter among a briefly presented string of 5 letters. This is important to the

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[1] Furthermore, the difference in cue-timing introduces a potential confound with the way that spatial attention can be directed to the target letter location (i.e., endogenous vs. exogenous orienting of attention – Posner, 1980; Theeuwes, 2014). We defer discussion of this issue to the General Discussion after presentation of the results obtained with the different types of cue tested in the present study.

extent that results obtained with the target-in-string identification task have been instrumental in motivating theories of the very first stage of orthographic processing, and understanding this initial phase of processing orthographic information is crucial for understanding the overall process of reading (see Grainger, 2018, for a review). Even more generally, the results of the present study should shed light on the key mechanisms involved in visual object identification whereby early location-specific processing of object features enables access to a location-invariant object identity (Bowers et al., 2016).

EXPERIMENT 1A

Design & Stimuli

This experiment employed a 2x2 factorial design. The two factors we manipulated were string location and cue type. String location was either fixed or variable. If the string location was fixed, it always appeared at the same location on the screen (at a central fixation point). If the string location was variable, however, it appeared either at the central fixation point, or to the left or to the right, maintaining the same vertical position. Letter targets were cued either before with an ordinal cue or after presentation of the stimuli with an underscore cue (ordinal vs. underscore). Each block corresponded to a single cell of this design: Fixed-Ordinal, Fixed-Underscore, Variable-Ordinal, Variable-Underscore. The order of the blocks was counterbalanced across participants. Furthermore, we balanced the position-in-string of the cued element. As such we used 4 conditions x 5 positions x 20 for a total of 400 trials, with 100 trials per block. Stimuli consisted of 100 5-character strings. The strings consisted only of consonants. These were drawn from a set of 14 medium- to high-frequency consonants (B, C, D, F, G, H, K, L, M, N, P, R, S, T). We excluded the low-frequency consonants J, Q, W, X, Y, Z. Strings were generated randomly to contain no repeated letters. All letters appeared in stimuli an equal number of times.

Procedure

Participants carried out a letter-in-string identification task. Prior to the experiment, all participants provided written consent. Participants were given instructions at the beginning of each block. In each trial, participants would first see either a central fixation cross (in the underscore cue condition) or a single digit (in the ordinal cue condition) for 1000 ms. Note that the ordinal cue condition indicated a target *position*, not a target *character identity*, which is what had been used in previous studies. This fixation was then replaced by the consonant string either at the same location (fixed trials and some variable trials) or offset 2 characters to the left or right on the same line (variable trials) for 100 ms. Strings were presented in upper-case letters in black font on a gray background, followed by a backward mask comprised of hash-marks (#) at the same position as the string until response. In the post-cue condition, one of the positions was indicated as being the target via an underline of the corresponding hash mark. Participants would then enter the letter which had been displayed at the cued position using the keyboard. Participants were encouraged to respond as accurately as possible. After response, there was a 1000 ms pause, followed by the presentation of the fixation for the next trial. Before the start of each block, participants were told in the instructions whether it would be an ordinal or underscore cue block, as well as whether or not the string would always appear in the same position. They would then complete ten practice trials with feedback before proceeding to the experiment itself. Trial order was randomized by participant. Data were collected online using the Labvanced platform (Finger et al., 2017). The experiment lasted approximately 35 minutes.

Participants

Ninety-nine[2] native speakers of English (46 female, 53 male; mean age 34.01 years (SD = 11.72)) were recruited via Prolific (www.prolific.co) to complete the experiment online. All reported having no literacy difficulties or language disorders.

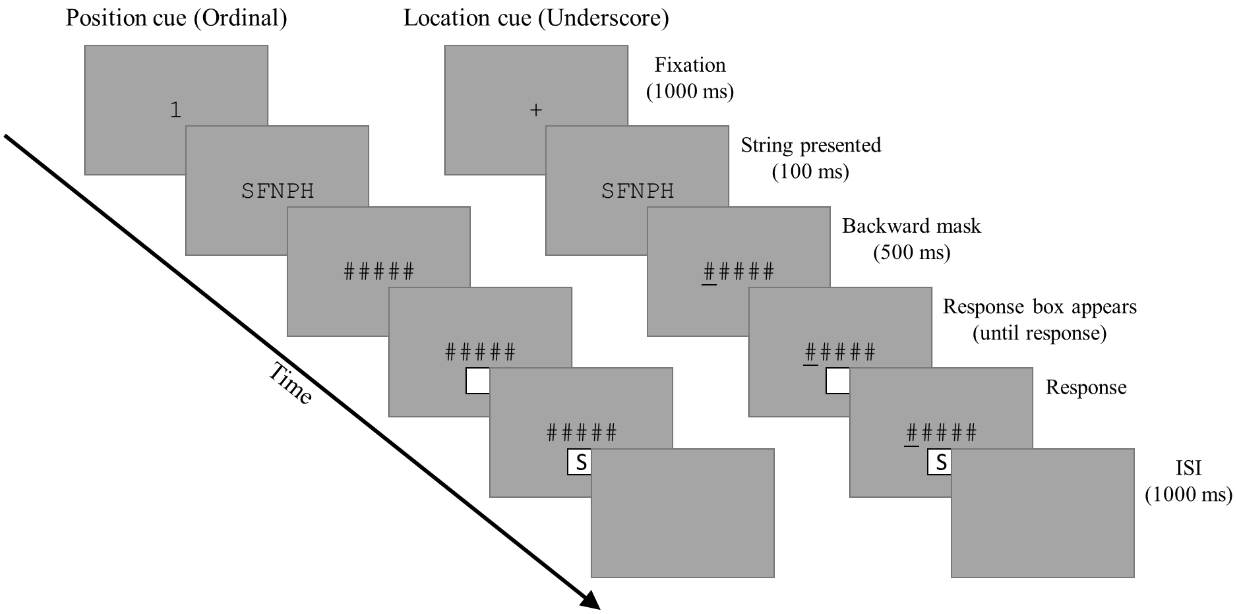

Figure 1. Trial schematic of Experiment 1 showing a trial from both the ordinal cue condition (left) and from the underscore cue condition (right) targeting the first letter slot. They are depicted as fixed-location trials. Font size is exaggerated.

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[2] We could not apply an a priori power analysis based on prior experimentation given that, to our knowledge, similar experiments do not exist. We therefore simply opted for large sample sizes in order to ensure sufficient power.

Analysis

We conducted a generalized (logistic) linear mixed effects regression (GLMER) with accuracy as the dependent variable. The model had a crossed fixed effects structure with cue type (ordinal vs underscore), and string location (fixed vs variable). We used an iterative process to arrive at our random effects structures, starting with the most complex and simplifying until the model converged in a non-singular fit. We included crossed random effects of item, position in string, and participant, as well as crossed by-participant crossed slopes for cue type and string location, and by-trial and by-position-in-string slopes of cue time. This was conducted using the glmer function in the lme4 package (Bates et al., 2015) in R (R Core Team, 2020). We report regression coefficients (*b*), standard errors (SE), and z-values). Fixed effects were deemed reliable if $|z| > 1.96$ (Baayen, 2008). We used the fixed-location ordinal cue condition as the reference[3].

Results

Based on 39,600 observations, participants had a mean accuracy of 64.7% (SD 10.4). We found significant effects of both cue type (higher performance in ordinal cue condition; *b*= -1.67, SE= 0.19, z= -8.68), and string location (higher performance in fixed location condition; *b*= -1.26, SE= 0.21, z= -5.97), as well as an interaction effect between cue type and string location (greater effect of cue type in the fixed location condition; *b*= 1.00, SE= 0.16, z= 6.30). Condition means are shown in Figure 2 (left panel).

EXPERIMENT 1B

Design, stimuli, and procedure

[3] All stimuli, presentation code, raw data, and analysis code are available on the OSF: https://osf.io/9678y/.

The design, stimuli and procedure of Experiment 1B were exactly the same as Experiment 1A, with one small adjustment. In the variable location condition, whereas strings were offset by *two* characters to the left or right in Experiment 1A, strings were offset by *four* characters in Experiment 1B, resulting in a greater overall distance from fixation of target letters in the shifted conditions.

Participants

One hundred native speakers of English (61 female, 37 male, 2 non-binary; mean age 33.19 years (SD = 11.24)) were recruited via Prolific (www.prolific.co) to complete the experiment online. All reported having no literacy difficulties or language disorders.

Analysis

We performed the same[4] GLMER analysis with Experiment 1B as Experiment 1A. We did a further GLMER analysis comparing the results of the variable location trials in Experiment 1B to those in Experiment 1A to see whether eccentricity distance (two or four characters), cue type (ordinal vs underscore), or string location (left, center, or right) had an impact on performance. We included experiment (which separates the 2-character offset from the 4-character offset trials), string location, and cue type as crossed fixed effects, and used crossed random effects of item, position in string, and participant, as well as by-participant slopes for cue type, offset distance, and string location. We used the ordinal cue of the center location of Experiment 1A as the reference.

Results

Based on 40,000 observations, participants had a mean accuracy of 58.9% (SD 11.2). We found the same set of effects as in Experiment 1A: significant effects of cue type (better accuracy in ordinal cue condition; b= -1.86, SE= 0.12 z= -15.37), and string location (better accuracy in fixed location condition;

[4] Due to non-convergence, the random slope of cue time by cued character was eliminated from this model.

b= -2.01, SE= 0.09, z= -23.30), as well as an interaction between the two (greater effect of cue type in the fixed location condition; *b*= 1.42, SE= 0.10, z= 13.80). Condition means are shown in Figure 2 (right panel).[5]

Combined Analysis of the variable string location condition in Experiments 1A & 1B

This analysis involved the factors cue type and string location (left, center, right). We found significant effects of cue type (better performance in the ordinal cue condition; *b*= -1.15, SE= 0.08, z= -14.29), experiment (better performance in the 2-character offset condition in Experiment 1A; *b*= -0.61, SE= 0.13, z= -4.56), and location on both the left (*b*= -1.52, SE= 0.17, z= -8.82) and the right (*b*= -1.02, SE= 0.17, z= -5.94) with performance on both sides being worse than in the center. We also found significant interactions between cue type and experiment (greater effect of offset distance in the ordinal cue condition; *b*= 0.38, SE= 0.11, z= 3.45), and cue type and string location on both the left (*b*= 0.75, SE= 0.09, z= 8.02) and the right (*b*= 0.57, SE= 0.09, z= 6.42), with greater effects of string location in the ordinal cue condition. We found a significant interaction between experiment and location on the left (*b*= -0.28, SE= 0.11, z= -2.49), but only marginal interaction on the right (*b*= -0.19, SE= 0.10, z= -1.89), with greater effects of offset distance on the sides than the center. We found a marginal three-way interaction between cue type, experiment, and location on the left (*b*= -0.25, SE= 0.13, z= -1.91) but not the right (*b*= -0.18, SE= 0.12, z= -1.43).

[5] Following the request of a reviewer we also provide information about the nature of errors in terms of their distance from the target letter location when the error was another letter in the string. This information is provided in online Supplementary Materials on the OSF (https://osf.io/9678y/), and the results are briefly discussed in the General Discussion.

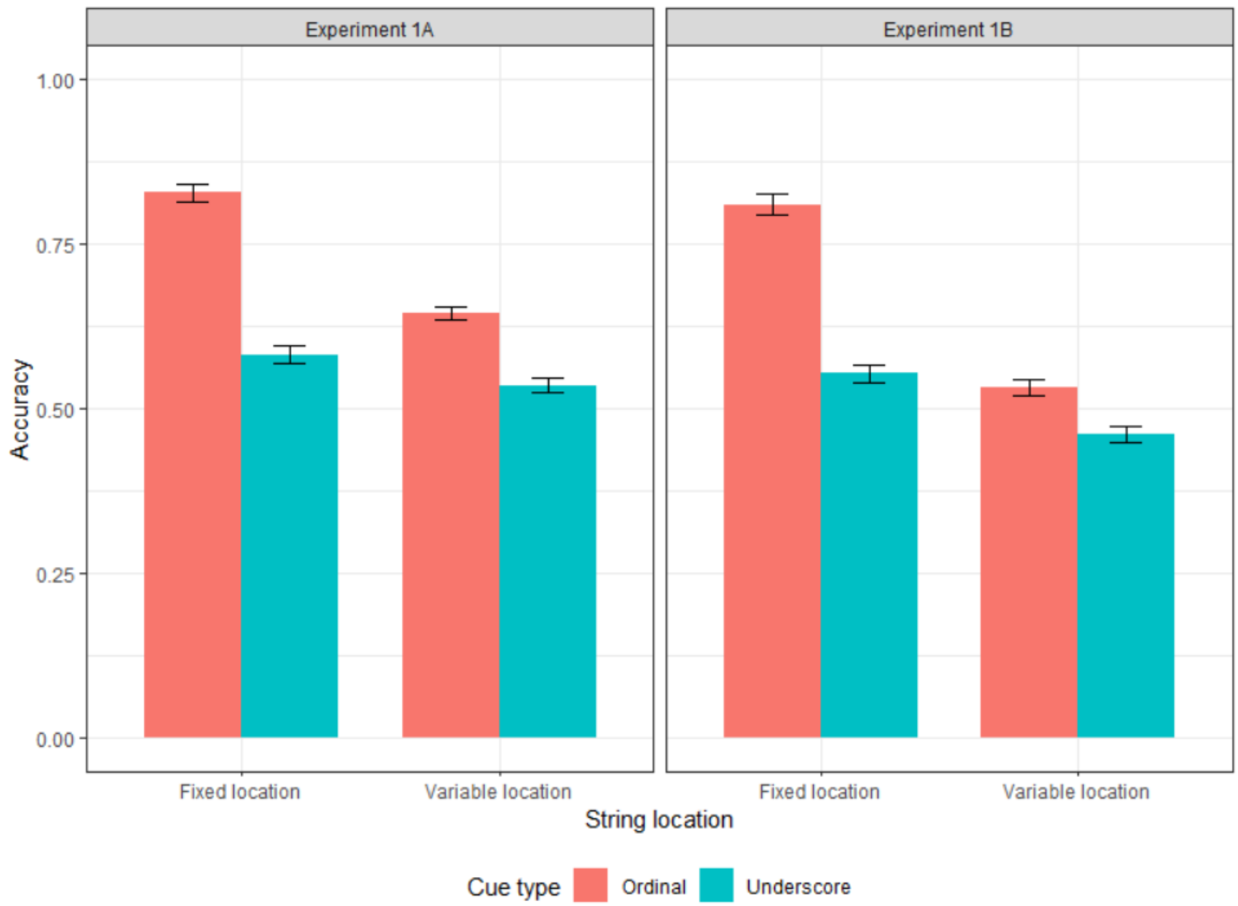

Figure 2. Accuracy by condition from Experiment 1A (left) and 1B (right). Note that the results of the variable location conditions represent the average across the three string positions (left, center, right). Error bars are within-participant 95% CIs (Cousineau, 2005).

Discussion

The results of Experiment 1 show a clear advantage for ordinal cues compared with underscore cues in letter-in-string identification accuracy, and an overall decrease in performance in the variable string location condition compared with the fixed location condition. As predicted, there was a bigger impact of string location variability in the ordinal cue condition. However, contrary to our predictions, accuracy was higher with ordinal cues than underscore cues. This is most likely due to the prior allocation of attention to the location of the up-coming target letter (ordinal cues were presented prior to the string of letters whereas underscore cues appeared after). It is also likely that the greater drop in accuracy in the variable string location condition for ordinal cues is due to the time required to locate the stimulus string prior to isolating the position of the target letter in the string. Comparing the results of the variable string location condition in Experiments 1A & 1B (see Figure 3) we also found an effect of degree of string displacement in the variable location condition, with a greater shift in location accompanied by lower accuracy. This drop in accuracy was statistically equivalent for the ordinal and underscore cue conditions. We also note that the effect of cue type in the variable string location condition was greater for centrally located strings. This again can be explained by ordinal cues requiring prior localization of the string of letters when these are shifted left or right.

This pattern of results can be explained by assuming, as was predicted, that read-out from activity in location-specific letter detectors is being used to perform the letter-in-string identification task independently of the type of cue, and that this activity can be modulated by endogenous orienting of attention when the cue is presented prior to the string of letters (pre-cueing). Given that the ordinal vs. location cueing manipulation was confounded with pre vs. post cueing in Experiment 1, in Experiment 2 we compared performance with the two types of cue when both were presented prior to the letter string. As mentioned in the Introduction, comparing ordinal and location post-cues was not considered, given the greater time required to process an ordinal cue.

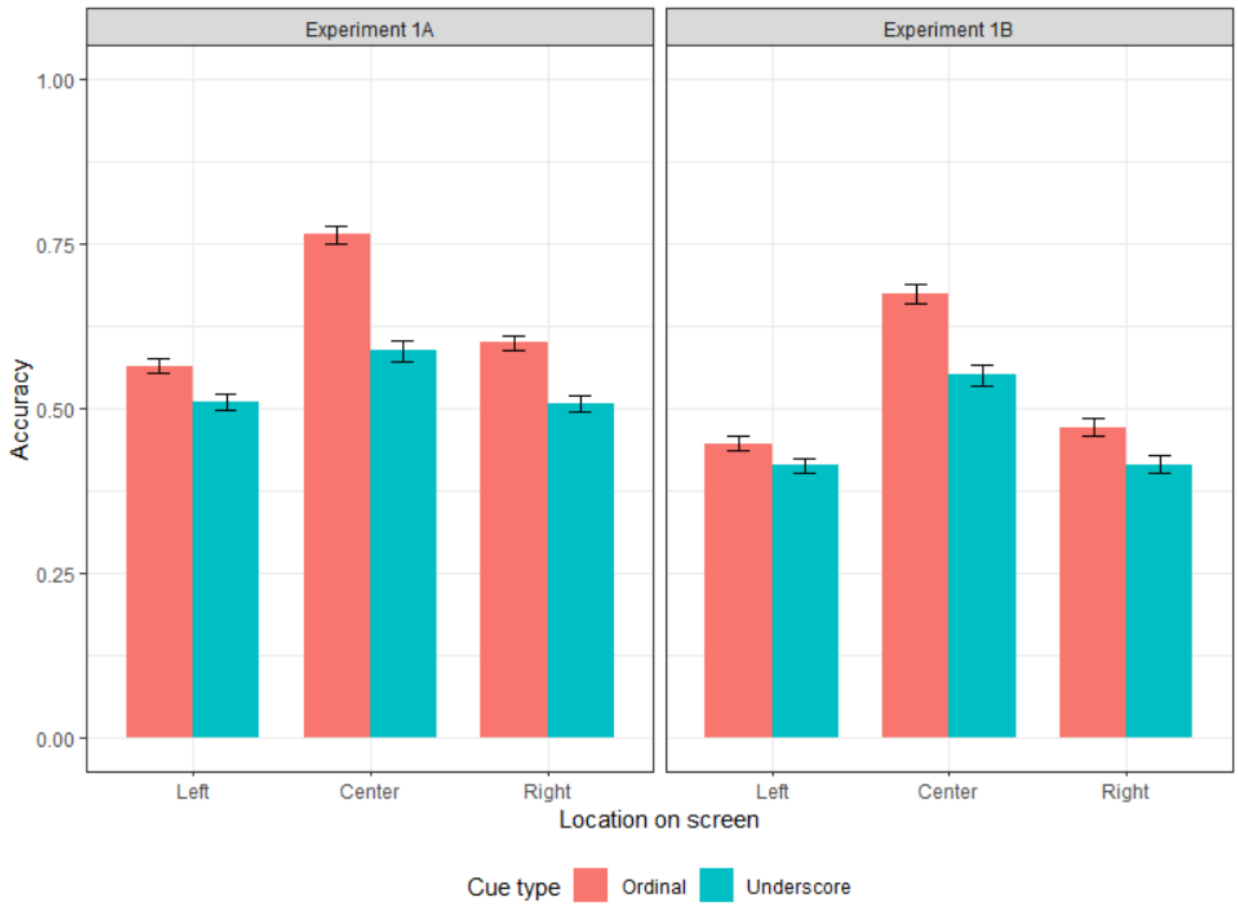

Figure 3. Accuracy in the variable string location trials from Experiment 1A and 1B separated by display location (left, center, right). Experiment 1A had an offset of two characters while 1B had an offset of four characters. The central location condition is included for completeness although these data were not analyzed. Error bars are within-participant 95% CIs.

EXPERIMENT 2

Design, stimuli, and procedure

The design, stimuli and procedure of Experiment 2 were the same as in Experiment 1B, except that there was no post-cue condition. Instead, the ordinal pre-cue blocks were the same, but the location post-cue was replaced by a pre-cue of the same form (5 hash-marks with one underscored). We kept the 4-character offset in the variable position condition as in Experiment 1B.

Participants

Ninety-seven native speakers of English (54 female, 43 male; mean age 35.42 years (SD = 11.37)) were recruited via Prolific (www.prolific.co) to complete the experiment online. All reported having no literacy difficulties or language disorders.

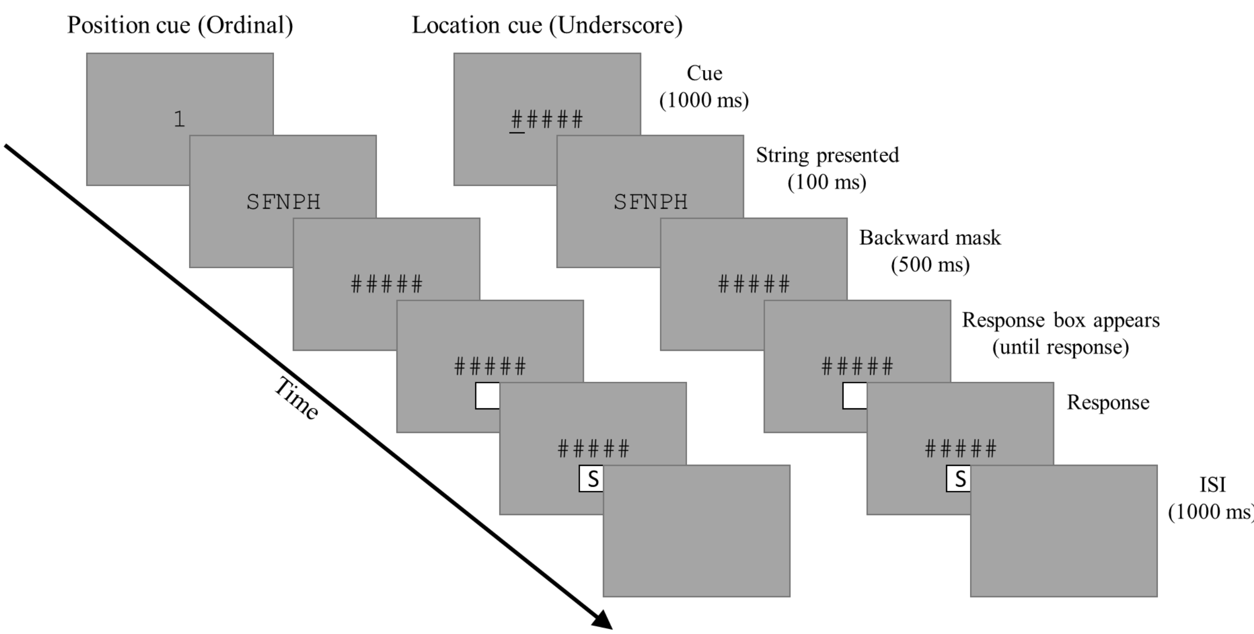

Figure 4. Trial schematic from Experiment 2. Ordinal cue (left) and underscore cue (right) trials are shown. Both depict the fixed string position condition. Font size is exaggerated.

Analysis

We performed the same GLMER analyses with Experiment 2 as Experiments 1A and 1B. We did a further GLMER analysis looking at the effect of pre- and post-cueing for the underscore cue trials from Experiments 1B (post-cued) and 2 (pre-cued). In this case we again used accuracy as the dependent variable with cue type (pre vs post), string location (fixed vs variable), and experiment as crossed fixed effects. We included crossed random effects of item, position in string, and participant, as well as by-participant crossed slopes for cue type and string location, and by-trial and by-cued character slopes of cue time. The fixed location, ordinal cue condition was used as the reference.

Results

Based on 38,800 observations, participants had a mean accuracy of 71.4% (SD 11.1). We found significant effects of both cue type (better performance for underscore cues; *b*= 2.13, SE= 0.29, z= 7.28) and string location (better performance in fixed location condition; *b*= -2.41, SE= 0.13, z= -19.23), as well as an interaction between the two (greater effect of string location on underscore cues; *b*= -2.13, SE= 0.16, z= -13.19). Condition means are shown in Figure 5.

Combined Analysis of Experiments 1B & 2

In order to compare the effects of underscore cues when presented at string offset (post-cueing, Experiment 1) and prior to string onset (pre-cueing, Experiment 2), we performed a combined analysis of Experiments 1B and 2 where all other conditions were identical. We found significant effects of cue type (better performance for ordinal cues; *b*= -4.27, SE= 0.34, z= -12.50), and string location (better performance in fixed location condition; *b*= -4.41, SE= 0.19, z= -23.17), and an interaction between the two (greater effect of cue type in fixed location condition; *b*= 3.79, SE= 0.20, z= 19.17). As can be seen in Figure 5, presenting underscore cues prior to string onset led to greater accuracy, and most of all when string location was fixed.

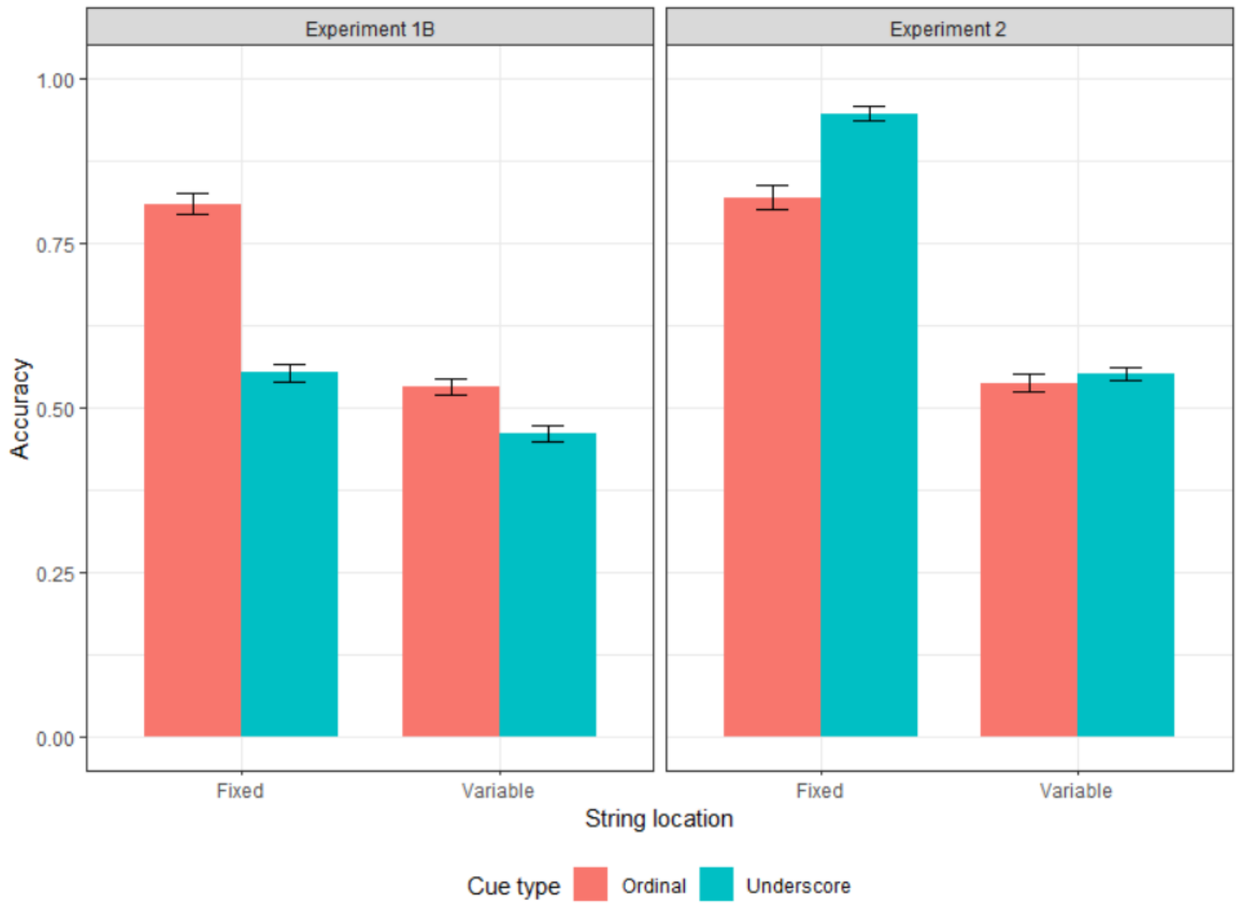

Figure 5. Accuracy of trials from Experiments 1B (ordinal pre-cue and underscore post-cue; left) and 2 (ordinal pre-cue and underscore pre-cue; right). Error bars are within-participant 95% CIs. Note that the results of the variable location conditions represent the average across the three string positions (left, center, right). The ordinal cue condition of Experiment 2 is a direct replication of that condition tested in Experiment 1B.

Discussion

Unsurprisingly, Experiment 2 provides a perfect replication of the results obtained with an ordinal pre-cue in Experiment 1B. More interesting is the fact that the underscore cue was now more effective than the ordinal cue, and particularly in the fixed string position condition (see Figure 5). Indeed, the shift from post-cueing to pre-cueing with an underscore cue brings the results more in line with those obtained with an ordinal pre-cue, with the exception of the even better performance seen with underscore pre-cues compared with ordinal cues in the fixed string location condition. The large drop in performance with underscore cues between the fixed and the variable string location in Experiment 2 is due to the fact that these cues did not indicate a target location in the variable string location condition, but the position of the target in the string of letters. This can be seen in Figure 6, where it is clear that the drop in accuracy in the underscore cue condition is driven by the trials where the string was shifted either left or right.

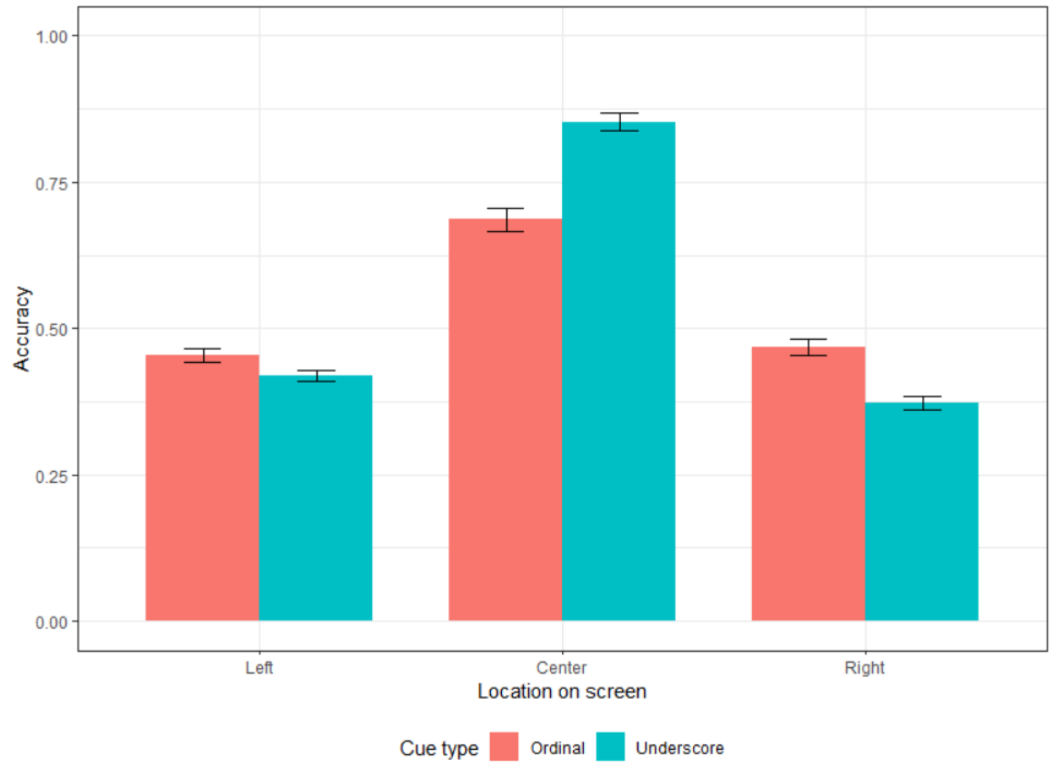

Figure 6. Accuracy of trials as a function of cue type in the variable string location condition of Experiment 2. Error bars are within-participant 95% CIs.

EXPERIMENT 3

In Experiment 3 we changed the nature of the underscore pre-cue in the variable string location condition, such that the mask covered all possible target locations and the underscore precisely indicated the target location in space rather than its position in the string. Otherwise, the conditions were the same as in underscore pre-cue condition of Experiment 2.

Design, stimuli, and procedure

As in Experiment 2 the string location could be fixed or variable, and we maintained the four-character offset in the variable string location condition. In Experiment 3, however, the cues were presented in the form of a string of 13 hash-marks. These 13 hash-marks indicated all of the possible letter locations on the screen in the variable string location condition. In the fixed string location condition, only the central five hash marks were cued. In the variable string location condition, any position (1 – 13) could be cued.

Participants

Ninety-nine native speakers of English (54 female, 45 male; mean age 31.14 years (SD = 9.68)) were recruited via Prolific (www.prolific.co) to complete the experiment online. All reported having no literacy difficulties or language disorders.

Analysis

We conducted a GLMER analysis using the underscore pre-cue data from Experiment 2 as well as the data from Experiment 3. We thus used accuracy as the dependent variable, with cue type (5 or 13 hashes) and string location (fixed or variable) as crossed fixed effects. We included crossed random effects of item, position in string, and participant, as well as by-participant crossed slopes for cue type and string location. The fixed string location condition of Experiment 3 was used as the reference.

Results

Based on 19,800 observations, participants had a mean accuracy of 76.6% (SD 20.4). We found significant effects of both cue type (better performance with the 5-hash cue; *b*= 2.60, SE= 0.35, z= 7.34), not string location (*b*= 0.42, SE= 0.27, z= 0.12), but an interaction between them (greater effect of string location in the 5-hash condition; *b*= -4.74, SE= 0.35, z= -13.53). Condition means are shown in Figure 7. Results for the variable location conditions in both Experiments 2 and 3 broken out by location are shown in Figure 8.

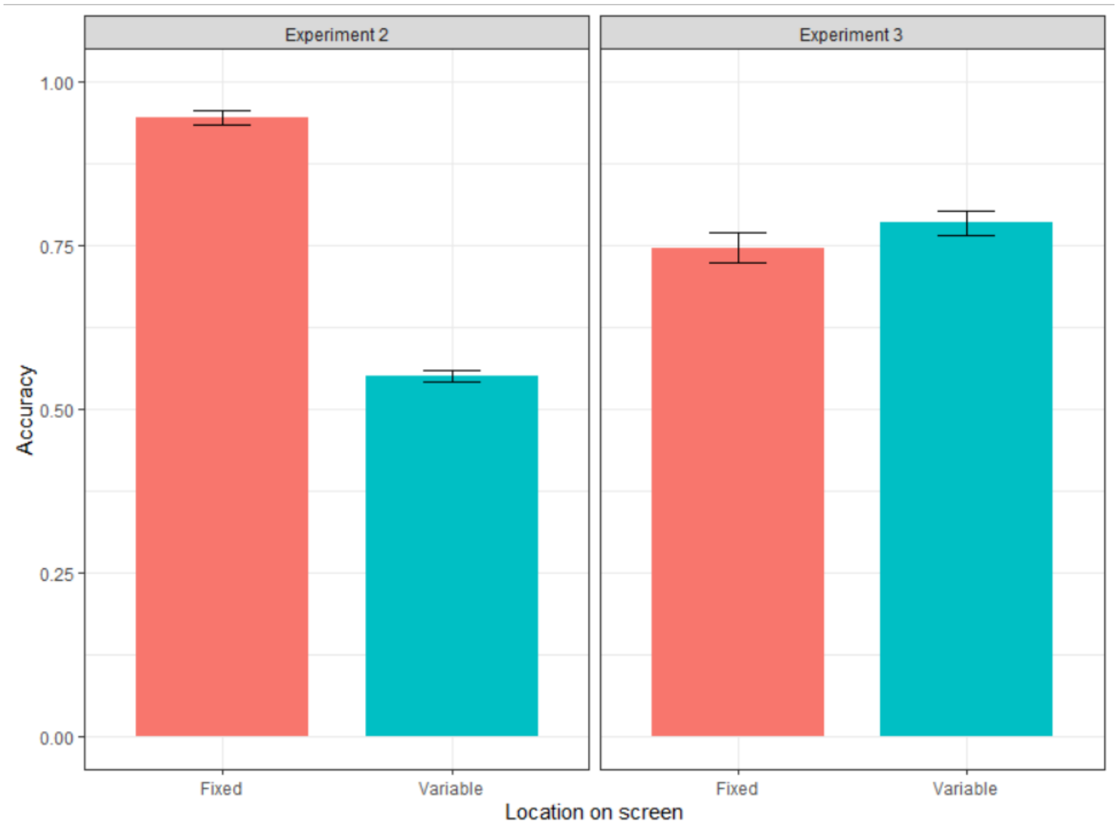

Figure 7. Accuracy of trials from the underscore pre-cue conditions tested in Experiments 2 and 3. Error bars are within-participant 95% CIs.

Discussion

The results of the fixed string location condition in Experiment 3 revealed a drop in accuracy compared with the same condition tested in Experiment 2 (94.6% in Exp. 2 vs. 74.7% in Exp. 3, $t = 7.62$, $p < .001$; see Figure 7). This suggests that locating the upcoming target position was harder when it was indicated using a longer 13 hash-mark mask compared with the 5 hash-mark mask used in Experiment 3. More interesting are the results obtained in the variable string location condition of Experiment 3. These clearly demonstrate that when the underscore pre-cue indicates a location in space (Experiment 3) as opposed to a position-in-string (Experiment 2), then accuracy matches that seen in the fixed string location condition. This result is again in line with the hypothesis that performance in the letter-in-string identification task is based on read-out from location-specific letter detectors.

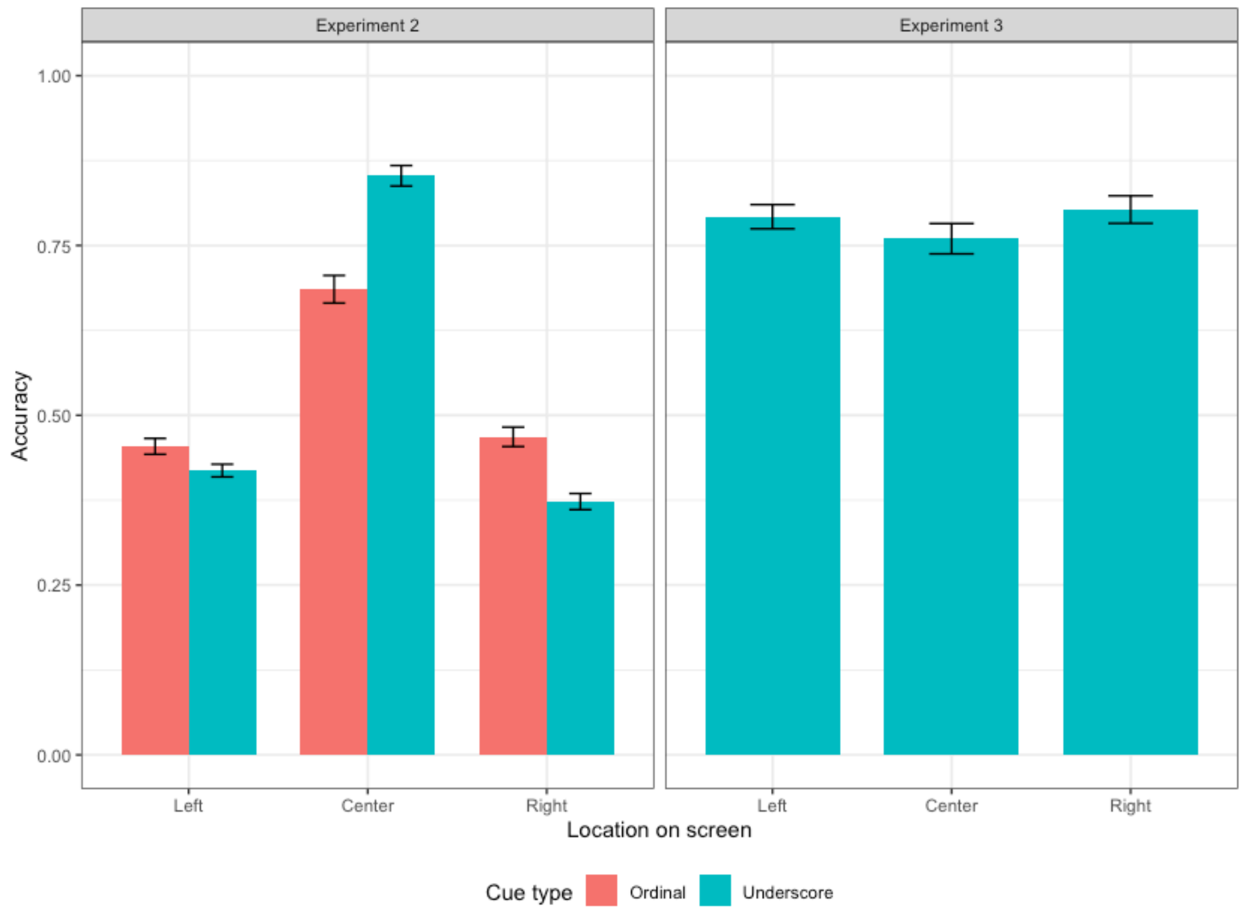

Figure 8. Accuracy of trials from the variable location conditions in Experiments 2 and 3. Error bars are within-participant 95% CIs.

GENERAL DISCUSSION

The starting point of the present study was the hypothesis that performance in the letter-in-string identification task with brief stimulus exposures (e.g., 100 ms) and backward masking, is driven by read-out from a bank of horizontally aligned location-specific letter detectors (for languages written with a horizontally aligned alphabetic script). These are thought to be developed with the aim to implement parallel letter processing in order to optimize visual word recognition, a key factor for becoming an expert reader. This is the first level of orthographic processing in the model proposed by Grainger and van Heuven (2004), and information processed at this level enables the subsequent computation of an ordered, location-invariant, set of letter identities that are used to identify words. We aimed to test this hypothesis by investigating the impact of different types of cueing procedure on letter-in-string identification, and notably the difference between an ordinal cue (e.g., identify the letter at the 2nd position in the string) and a location cue, where the target letter is indicated by some physical marker (an underscore in the present study). We predicted that location cues should be more effective than ordinal cues, and particularly when the location of the string varied from trial-to-trial along the horizontal axis.

In Experiment 1, we indeed found that string location had a bigger negative influence on performance with ordinal cues. However, contrary to our prediction, ordinal cues were found to be more effective than underscore cues. This finding was interpreted as evidence that the ordinal cue, presented prior to stimulus onset, was being used to guide attention to the upcoming target letter location. This was not possible with underscore cues since these were presented at stimulus offset, as is standard in letter-in-string identification studies. The greater negative impact of string location variability in the ordinal cue condition was then interpreted as evidence that the string had to be localized prior to isolating the position of the target letter in the string. This interpretation was supported by an analysis of the effects of string location (left, center, right), that revealed that the drop in performance with ordinal cues in the variable string location condition compared with the fixed string location condition occurred mainly when strings were shifted to the left or to the right.

In order to provide a more direct comparison of performance under ordinal vs. underscore cueing procedures, in Experiment 2 these were both presented prior to string onset. Here, letter-in-string identification accuracy with underscore cues was greatly increased compared with Experiment 1, to the extent that underscore cueing now outperformed ordinal cueing, but only in the fixed string location condition (see Figure 5). This was due to the fact that in the variable string location condition the underscore cue did not cue a location, but rather a position in the string. Due to this, performance with underscore cues was influenced by string location in the variable string location condition, with performance dropping when the string was shifted left or right (see Figure 6). In Experiment 3 the underscore pre-cue indicated target letter location in both the fixed and the variable string location conditions, and here we found that performance was roughly equivalent in these two conditions.

We conclude that both types of cue (ordinal and underscore) are used to guide read-out from a bank of horizontally aligned location-specific letter detectors, and that under appropriate pre-cueing conditions attention can be directed to the location of the up-coming target letter hence improving letter identification accuracy. The ordinal cues used in the present study most likely acted as an endogenous attentional cue, analogous to the left and right arrow cues in the seminal work of Posner and colleagues (see Posner, 1980, for a review of the early research on visual attention). In our study, attention could be directed to a particular location in space, and more or less precisely as a function of whether or not the string of letters remained at a fixed location. We suspect that the underscore cues used in the present study also acted to direct endogenous attention to a particular location in space, and particularly when these were presented prior to string onset (pre-cueing). Differences in the effectiveness of ordinal and underscore cues might therefore reflect how well attention could be directed to a specific location as a function of cue-type and string location variability.

The large impact of string location variability found in all three experiments, except for the pre-cued underscores in Experiment 3, provides important support for our main hypothesis: that target-in-string identification is driven by read-out from location-specific letter detectors – the first level of processing in the Grainger and van Heuven (2004) model. Read-out from a location-invariant letter order code should have been more effective with an ordinal cue than an underscore cue, at least when string location was held constant. This was clearly not the case when cue timing was matched for the two types of cue (Experiments 2 & 3). However, most models of orthographic processing choose to ignore the issue of location invariance, that is how gaze-centered or retinotopically encoded visual information of some form makes contact with a more abstract location-invariant higher-level representation. As noted by Bowers et al. (2006), this is an issue of central importance to models of visual object identification, including written words. We follow Bowers et al. in suggesting that location-specific information makes contact with a unique higher-level location-invariant object representation. We further propose that for orthographic processing and reading, the initial phase of location-specific processing involves letter identities which are hypothesized to correspond to the complex visual features that form object parts in models of visual object identification (Biederman, 1987).

Finally, we provide an analysis of the types of errors produced by participants in online Supplementary Materials. Unsurprisingly, the distance from the target location was the primary factor determining whether or not another letter in the string would be reported in error, with the majority of such reports involving adjacent letters and their number diminishing as distance increased. More interesting is that participants were more likely to report a letter to the left of the target than to the right and particularly when the letter string was shifted to the left. This pattern fits with the modified receptive field hypothesis proposed by Grainger and colleagues to account for visual field differences in accuracy in letter-in-string identification (Chanceaux & Grainger, 2012; Chanceaux et al., 2013; Grainger et al., 2010; Tydgat & Grainger, 2009). According to the most refined version of this hypothesis (Chanceaux et al., 2013), the receptive fields of location-specific letter detectors are more asymmetric for detectors that receive information from the left visual field than those that receive information from the right visual field. That is, the classic oval shape of receptive fields, with their typical inward-outward asymmetry that characterizes visual object crowding (Pelli et al., 2004; Whitney & Levis, 2011), would extend more to the left for letter detectors left of fixation. The increased asymmetry toward the left in the left visual field accounts for the greater number of incorrect reports of letters located to the left of targets presented in the left visual field in the present study.

In sum, we have demonstrated how a manipulation of the type of cue used to indicate target letter location in the letter-in-string identification task can be used to better understand the mechanisms involved in performing this task. When the task involves briefly presented, pattern-masked, horizontally aligned consonant strings, we conclude on the basis of prior findings and the present results that read-out is based on a reading-specific mechanism for associating letter identities with locations along a line of text. We predict that the same pattern of findings should be found with digit strings, but not with other kinds of stimulus arrays. Future research could provide further tests of this hypothesis by comparing cueing effects with letters / digits and other kinds of stimulus array, and with horizontally arranged and vertically arranged letters.

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Open-science practices

The raw data as well as the scripts used for preprocessing and analysis and Supplementary Materials are available on the OSF: https://osf.io/9678y/

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