Serial Binding Mechanisms in Position-Specific Recall of Letters in (Non)Words

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Abstract

The present study acts as a follow-up on previous studies investigating serial binding as a mechanism of position-specific letter-recall through utilization of n-th letter retrieval tasks. Some of these studies found an unexpected relative performance peak at the third position of Dutch nonwords, while other studies found that centered warning signals did not induce their hypothesized effects on German and English nonwords. The present study investigated the effects of centered and distributed warning cues on position-specific letter-recall accuracy in Dutch (non)words. Furthermore, exclusively nonwords with a low-frequency were utilized so as to explore an alternative explanation of the earlier found performance peak at the centre of Dutch nonwords. The previous finding that the centered warning signal *did not* induce a relative performance peak was replicated, but letter-recall accuracy took on a U-shape across positions in nonwords cued with distributed and centered warning signals, rather than the expected hook-shape. An explanation of this finding is given in terms of the tail-frequencies of nonwords, which were not controlled. The present study is consistent with a serial binding explanation of position-specific recall, but further research is needed to confirm the role of tail-frequencies in inducing the U-shaped distributions found in nonwords.

Keywords: serial binding, letter recognition, n-th letter task, orthographic processing

Serial Binding Mechanisms in Position-Specific Recall of Letters in (Non)Words

It is a remarkable fact of human cognition that our conscious experience of reading texts is one characterized by integrality and continuity. That is, as one examines a text, each word is perceived as a whole, rather than an assembly of shapes. And as one reads, each successive word is scanned from left-to-right with apparent ease. This subjective experience, however, fails to accurately depict the physical and cognitive processes involved in reading. Indeed, from an empirical point of view, as one scans through each successive word, the eyes make up to five saccadic movements per second, and the detailed vision provided by the fovea encompasses merely one or two short words per fixation (Dehaene, 2009; Kemmerer, 2014).

Research into human language perception and recognition, remarkably, has moved well beyond basic facts of sensory physiology. On a structural level – i.e., at the level of underlying and causally effective material parts, much work has been done on the neural substrates responsible for the detection and recognition of letters and words (e.g. Dehaene et al., 2005), while on a functional level – i.e., the level of goal-oriented information processing, cognitive psychologists have endeavoured to model the reception, integration and understanding of information contained in (written) language (Grainger, 2008). Broadly speaking, this area of research has been quite successful. The interactive activation model (IAM) (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982), for one, provided an explanation of why real words are more efficiently identified than nonwords (i.e., a random string of letters) (Cattel, 1886), and why subjects are better at identifying a constituent letter of a real word than of a nonword (Reicher, 1969; Wheeler 1970) – a phenomenon known as the *word superiority effect.* Consecutive efforts, such as the SERIOL and spatial coding model (SCM) (Davis, 2010; Whitney 2001), not only improved on biological plausibility but also provided accounts of phenomena left unresolved by the IAM, such as transposition and relative position priming (Humphreys et al., 1990; Peressotti & Grainger, 1999).

Clearly, these models have shed much light on the capacity of word-recognition. But not all mechanisms involved in orthographic processing are properly understood. The task of retrieving a letter at a specific position in a word, for instance, is easily accomplished, yet the mechanisms facilitating this process remain unknown. The present study aims to investigate the plausibility of a possible solution to this problem by extending on previous studies which utilized the n-th letter task experimental paradigm, whereby participants are asked to perform the simple task of retrieving letters at specific positions in (non)words.

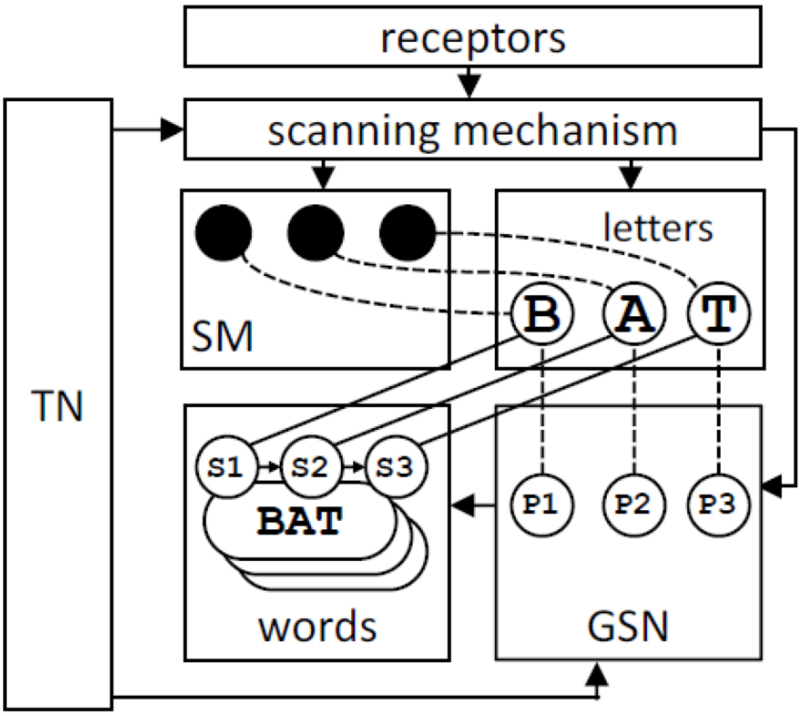
Some empirical research on position-specific recall has been conducted (Bhouri, 2018; Buijsman, 2019; Donelan, 2018; Freericks, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019; Whittaker, 2019), but it has had little use of models like the IAM, SCM and SERIOL model. Indeed, while these models effectively elucidate phenomena concerning word-recognition, they fail to disclose the mechanisms which enable an individual to retrieve a letter at a specific position in a word. Specifically, the IAM assumes *position-specific slot encoding* – i.e., distinct representations of possible letter position-identity combinations (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). This is problematic, as it is implausible that there exists a specific neural substrate for any possible position-identity combination (e.g., letter R at position 2, and so forth). In fact, such encoding would lead to an inefficient number of representations, and make the realization of any one representation unlikely due to neurological interference – a circumstance that has been coined *superposition catastrophe* (von der Malsburg, 1981). Position-specific slot encoding, thus, not only fails to explain *how* a letter identity gets associated with a specific position but is implausible altogether. As could be expected, alternative models have avoided this type of encoding: the SERIOL model eliminates position-specific representations through encoding of (ordered) bigrams (Whitney, 2001), while the SCM proposes representations of relative letter position through phase-dependent excitation levels (Davis, 2010). While biologically plausible, these models, too, remain restricted to explaining phenomena concerning word-recognition, and fail to specify the mechanisms which might facilitate position-specific recall of letters.

A possible solution to the abovementioned problem lies in the specification of a set of mechanisms which elucidate how the brain can achieve position-specific recall without assuming permanent, position-specific encoding. Previous experimental work on this topic has therefore focused on de Vries' (2016, 2020) conceptual network, which postulates a biologically plausible mechanism of letter position-identity binding (Bhouri, 2018; Buijsman, 2019; Donelan, 2018; Freericks, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019; Whittaker, 2019). The conceptual network builds forth on the notion that *cell-assemblies* – i.e., clusters of neurons characterized by high mutual synaptic strength – underly mental representations of concepts, or *memory traces* (de Vries, 2016, 2020). The existence of cell-assemblies is implied by Hebb's learning rule, which states that coincidental activation of interconnected neurons results in increased connectivity between them (Hebb, 1949; Huyck & Passmore, 2013). This rule also implies that cell-assemblies must have a *critical threshold*. That is, a level of activation at which it will necessarily rise to its maximal excitation level; a process facilitated by the self-reinforcing excitation patterns within the cell-assembly. In the conceptual network, sub-threshold activation of a cell-assembly is theorized to correspond to a state of priming, while supra-threshold activation is thought to correspond to the appearance of a representation in working memory (de Vries, 2020).

Each node in the conceptual network represents a memory trace (e.g., a representation of a word or letter), which can equivalently be seen as a cell-assembly at the structural level. As can be seen in Figure 1, the nodes representing letter identities can form various connections, with solid lines represent permanent connections and dashed lines representing temporary connections (i.e., binding). The letter nodes can get temporarily bound to locations in the spatial map (SM), as well as to nodes representing sequence (e.g., first, second, and so forth) in the global sequence network (GSN). The SM ensures binding between letter identities and their proper location through excitation patters within the map, the spatial features of which correspond isomorphically to the spatial properties of the external input which cause them. Temporary connections between nodes are thought to form when two cell-assemblies from a shared context engage in simultaneous activation, whereby the condition of a shared context is satisfied if there is a subnetwork priming the two cell-assemblies prior to their concurrent activation. The sum activation level of letter nodes in the conceptual network is not only determined by *bottom-up* excitation (i.e., activation from sensory input) but also *top-down* excitation from the word level, as is illustrated by the solid lines connecting the word module ('BAT' in the figure) to the appropriate letter nodes (see Figure 1). Letters which constitute a word, thus, receive more activation than those who do not, especially when the word node reaches its critical threshold (at which point it is perceived) – explaining the earlier mentioned word superiority effect.

Figure 1

The Conceptual Network



Note. Visual representation of the conceptual network, including a spatial map (SM), global sequence network (GSN) and task network (TN). Solid lines represent activation between modules by means of permanent connections, while dotted lines represent temporary connections (i.e., binding). Image retrieved from de Vries, P. H. (2016). Neural binding in letter- and word-recognition. In K. E. Twomey, A. Smith, G. Westermann & P. Monaghan (Eds.), *Neurocomputational models of cognitive development and processing: Proceedings of the 14th neural computation and psychology workshop* (pp. 17- 33). New Jersey: World Scientific, 2016.

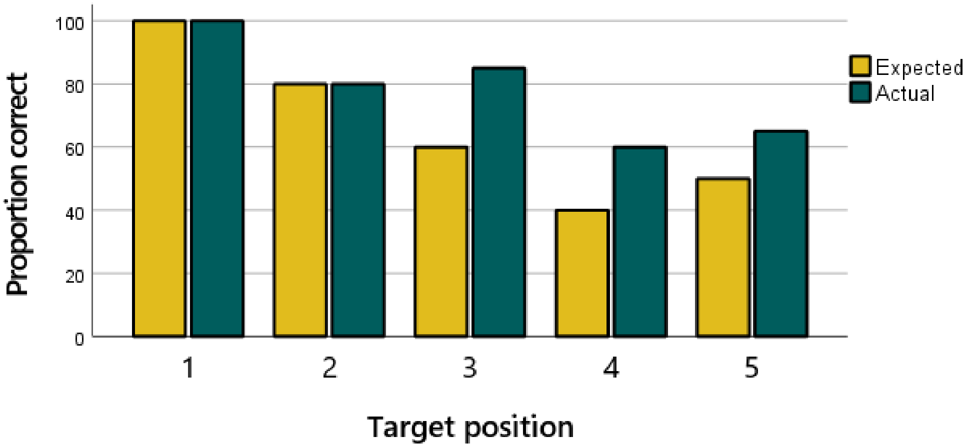
When the conditions of binding are met, a pair of cell-assemblies enters a state of *spike resonance,* meaning that the spike patterns within the cell-assemblies are caused to be in phase with one another. This state is then thought to facilitate the temporary connection between cell-assemblies through existing neural pathways. These binding processes cannot occur simultaneously, however, as spike resonances would suffer neural interferences. The conceptual network therefore includes a scanning mechanism, which ensures *serial binding*. It does so by selecting series of excitation pairs consisting of two cell-assemblies, which in the context of reading represent letter identity and letter position. By releasing only one excitation pair at a time (i.e., serially), binding between cell-assemblies can occur without disruption.

The conceptual network avoids the problem of superposition catastrophe through avoidance of permanent, position-specific encoding. Naturally, this entails the problem of how letters can be perceived at their correct position. As outlined above, however, this problem is solved by specifying a biologically plausible mechanism of temporary binding between cell-assemblies. Indeed, these mechanisms explain how the brain ‘knows’ when two cell-assemblies should form their temporary connection (simultaneous activation and a shared context), and how the connection itself is established (spike resonance). Consequently, the conceptual network is applicable to the phenomenon of position-specific recall and eligible to empirical scrutiny.

Using the conceptual network as their foundation, the earlier mentioned studies on position-specific recall assumed that there must be an association between the strength of letter position-identity binding and letter-recall accuracy. Indeed, it was reasoned that the serial nature of binding in the conceptual network implies a time delay amidst the binding processes of consecutive positions, signifying decreased strength of binding at each consecutive position due to the occurrence of *neural decay*. At the last position, conversely, a *reverberation effect* ensures relatively strong binding in virtue of their not being a next position to transfer activity to. One set of studies tested this effect for Dutch, English and German words by employing a n-th letter task, in which participants were briefly presented with five-letter words and nonwords and thereafter asked to identify a letter at a specific position (Buijsman, 2019; Mudogo, 2019; Pink, 2019; Schwartzkopf, 2019; Whittaker, 2019). Since the constituent letters of words receive strong top-down activation from the word level, letter-recall accuracies were predicted to be high at each position of the words. Indeed, results indicated a uniform distribution of letter-recall across positions with high overall accuracies. Nonwords, which lack this top-down activation, were expected to resemble a hook-shaped distribution, as the serial nature of binding implies a relative decrease from P1 to P4 and a relative increase from P4 to P5. The studies utilizing German and English (non)words were largely confirmative of this prediction (Mudogo, 2019; Pink, 2019; Schwartzkopf, 2019). The two studies utilizing Dutch (non)words (Buijsman, 2019; Whittaker, 2019), however, found a relative performance peak at P3 in Dutch nonwords, thereby contradicting their hypothesis. For a visual representation of the expected vs the found distribution of recall accuracies found in Dutch nonwords, see Figure 2 below.

Figure 2

Expected vs Found Distributions in Dutch Nonwords



Note. Yellow bars represent the expected letter-recall accuracies (Y-axis) across letter positions (X-axis), while blue bars represents the actual distribution of letter-recall accuracy found in the studies by Buijsman (2019) and Whittaker (2019).

A possible explanation of the abovementioned results lies in the role of attention. Certainly, increased activity at a specific position implies higher excitation levels at the corresponding location in the SM, thereby increasing strength of binding and thus recall accuracy. If participants in the Dutch studies, therefore, were disproportionally focused on the centre position, then this could have induced the found performance peak. Insight into this explanation can be derived from a set of studies which manipulated attention in a similar n-th letter task (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Seibel, 2018). In these experiments, participants' attention was manipulated by cueing the (non)words with a warning signal, which could either be distributed or centered. Distributed warning signals were thought to distribute attention equally across positions, while centered warning signals were thought to focus attention at the centre position of a (non)word. Due to the strong top-down activation that words receive, the effects of attention cues were predicted to be negligible for words; top-down activation ensures high accuracy at each position in any case. The experiments were largely confirmative of this prediction. For nonwords cued with a distributed warning signal, the effects of attention, too, were expected to be negligible. Indeed, since attention is evenly scattered across positions, the earlier discussed hook-shaped distribution is implied by serial binding. Again, results were in support of this hypothesis. The crucial prediction, however, was that the centered warning signals would induce a relative performance peak at P3 of nonwords due to increased attention at the corresponding location in the SM. These studies, however, found no such effect. Rather, the distribution of the nonwords resembled the hook-shaped distributions found in the earlier mentioned studies (Mudogo, 2019; Pink, 2019; Schwartzkopf, 2019).

The purpose of the present study is twofold. Firstly, warning signals identical to those utilized in the abovementioned studies are included in order to test their effects on Dutch, rather than English or German, (non)words. As mentioned, earlier studies found no significant performance peaks induced by the centered warning signals, but it is not clear whether this is a language-specific phenomenon. If this effect is specific to the Dutch language, then it might simultaneously provide insight into why a relative performance peak was found by Buijsman (2019) and Whittaker (2019) since these studies utilized exclusively Dutch (non)words. In addition, the present study considers the frequency of particular letter combinations at the heads (i.e., first three letters) of nonwords in their corresponding language – or the 'head-frequency' – on letter-recall accuracy. Specifically, it is reasoned that high-frequency heads (i.e., common letter combinations) may increase recall accuracy through increased top-down activation, while low-frequency heads are thought to exert no such effect. Relating this back to Figure 1, it is thought that high head-frequencies activate word nodes containing matching letter combinations – e.g., a nonword with the head 'SOR' may activate the word nodes 'sorbet', 'sorry', and so forth – which in turn would activate their associated letter nodes. Were this the case, then the earlier found performance peak at position three in Dutch non-words could be explained in terms a bias in the used set of Dutch nonwords with target position three, whereby the nonwords in this set tended to have a relatively high head-frequency. Accordingly, the present study utilizes a similar n-th letter task but controls for the head-frequency of nonwords by ensuring that all selected nonwords have a *low head-frequency*.

Having noted these variables, the following hypotheses can be formulated: I) For nonwords cued with a centered warning signal, a relative performance peak at P3 is expected due to increased activity at this location in the SM. II) Nonwords cued with the distributed warning signal are predicted to take on a hook-shaped distribution due to the effects of neural decay and reverberation. That is, we predict a decrease in letter-recall accuracy from P1 to P4 and an increase from P4 to P5. III) Letter-recall accuracy is expected to be high across all five positions in words cued with both the centered and the distributed warning signal due to strong top-down activation (especially relative to the nonwords). As letter-recall accuracy is expected to be near-optimal at each position, no differences between consecutive positions are predicted. Accordingly, a three-way interaction between word-type, position and warning signal is expected, meaning that the effects of any of the independent variables depends on the level of the others.

Notably, the present study is embedded within a series of experiments performed by collaborators. A study by Seppälä (2022) reflects the design of the present study, except that English, rather than Dutch, (non)words are employed. The hypotheses of this experiment correspond to the hypotheses outlined above. Two studies utilizing words and both high- and low-frequency nonwords, all cued with a centered warning signal, predict that low-frequency nonwords will induce low letter-recall accuracies relative to high-frequency nonwords (Gontija-Santos Lima, 2022; Beintema, 2022). Effects of the centered warning signal are therefore predicted to be negligible in high-frequency nonword trials, while it is predicted to induce a relative performance peak at P3 of low-frequency nonwords. Two studies utilizing exclusively high-frequency nonwords, cued with both the centered and distributed warning signal, too, predict that the effect of the centered warning signal is negligible in high-frequency nonword trials (Bosutar, 2022; Hennink, 2022). The nonwords in this study are therefore predicted to take on a hook-shaped distribution. All of the abovementioned studies predict no significant differences between consecutive positions in words cued with both the centered and the distributed warning signal due to high recall accuracy at each position.

Method

Participants

The experiment obtained data from three groups of participants. A group of paid participants was recruited via the platform Prolific (Palan & Schitter, 2018), who were awarded £2 for their participation. This group consisted out of four males with a mean age of 22 (SD = 1.41). In addition, a group of first-year BSc. Psychology students at the University of Groningen participated. This group consisted out of 22 females and 6 males with a mean age of 20 (SD = 2.61), who were awarded student-credits for their participation. Lastly, a group of volunteers consisting out of 8 males and 6 females participated. This group had a mean age of 27 (SD = 10.3). Accordingly, the total sample size was 46, consisting of 28 females and 18 males with a mean age of 22 (SD = 6.63). All participants spoke Dutch as their native language. The study was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences, Department of Psychology, at the University of Groningen. All participants signed an informed consent before participating.

Design

A 2x2x5 design was employed with independent variables word type (two levels: word and nonword), attention (two levels: distributed and centered) and position (five levels; one for each possible position). Accordingly, there were 20 conditions in total. The dependent variable was letter-recall accuracy, which was measured as the proportion of correct responses per experimental condition per participant. As noted, the head-frequency of nonwords was controlled for by selecting exclusively low-frequency nonwords.

Materials

Selection of the words was done by selecting pairs of five-letter Dutch words differing only at their target position (i.e., the position to be recalled in the n-th letter task) from the same word set as utilized by Buijsman (2019) and Whittaker (2019), which was originally derived from the CELEX Centre for Lexical Information (2001) database. Words were selected in pairs so as to minimize the effect of subjects inferring the target letter through its surrounding letters, which would be relatively likely to happen were there only one plausible letter to fill in (Reicher, 1969). For example, the words “feest” and “beest” formed a pair with target position one. For each target position, a set of 28 word pairs was selected. All selected words were ensured to have a frequency of > 7 per million existing words, thereby increasing the probability that words would in fact be perceived as such by the participants.

In order to form the nonwords, letters of the selected words were scrambled, with exception of the target letter, which always remained the same. By scrambling the selected words and keeping the target letters the same, it was ensured that the overall frequencies of letters and the letter identities of target letters was held constant between the sets of words and nonwords. This way, effects can be more confidently attributed to letter position and word-type, rather than letter identity frequency. Words within a pair were scrambled isomorphically to one another. For instance, ‘feest’ and ‘beest’ were scrambled to form ‘ftese’ and ‘btese’. In scrambling the letters, the head-frequencies of nonwords were checked against the occurrences of head-frequencies in existing Dutch words included in the CELEX database. Since the design utilizes exclusively low-frequency nonwords, nonwords were formed such that their head-frequency was minimized; with a few exceptions, all heads were non-existent in the Dutch language. This procedure resulted in the selection of five sets consisting of 28 low-frequency nonword pairs, with one set for each target position.

For each target position, a participant was presented with a set of six words and a set of six low-frequency nonwords. The abovementioned procedure resulted in enough (non)words to form four sets of words and four sets of nonwords per target position. The sets were therefore distributed across participants, so that different participants were presented different sets. As noted, participants were presented with six trials per experimental condition. As this was a 2x2x5 design, there were 20 experimental conditions in total. Accordingly, there were four sets of words for the 10 word conditions and four sets of nonwords for the 10 nonword conditions. In forming these sets it was ensured that they had comparable head-frequencies through inspection of the values of their quartiles. This way, unwanted effects caused by variability between sets was minimized. The remainder of (non)words were used for the practice blocks.

Procedure

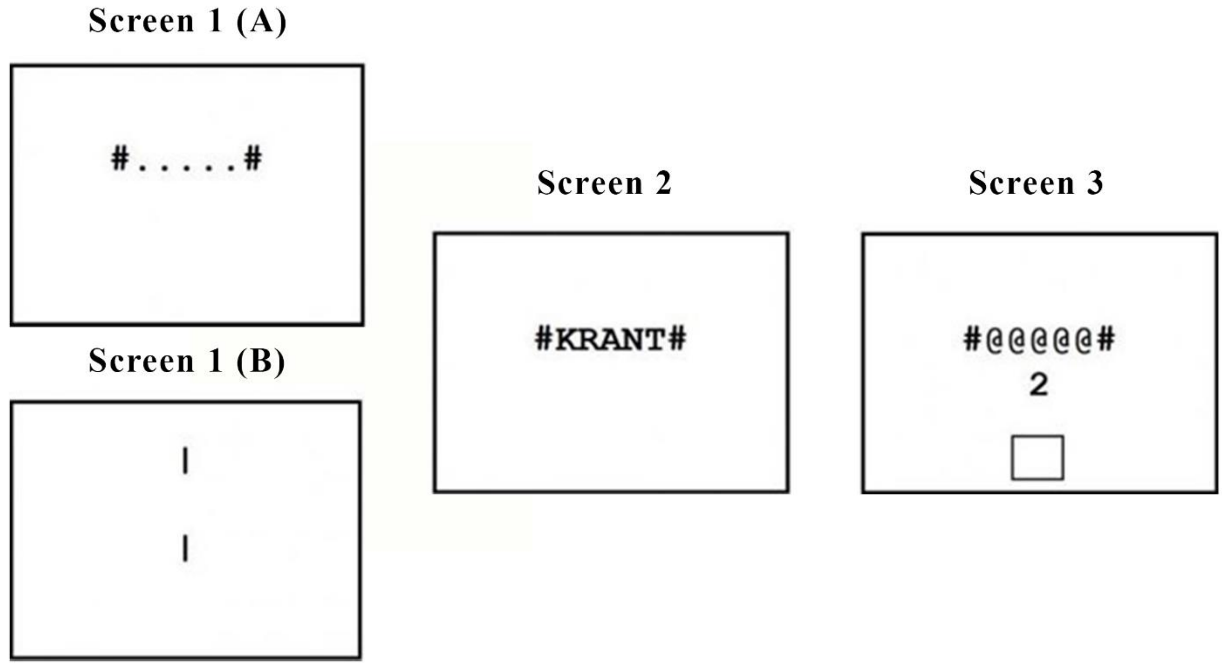
Due to COVID related circumstances, participants performed the behavioural experiment in an environment of their own choosing. The participants were instructed to find a quiet environment and to perform the experiment on a laptop / PC. Before starting the experiment, participants were presented with information relevant to their participation through Qualtrics (Qualtrics, Provo, UT). That is, they were notified that their age, sex and performance on the task would be collected, and were informed about the possible consequences of participation. Furthermore, they were given the email address of the principal investigator in case of any questions. Consecutively, an informed consent had to be signed. After completion of the informed consent, participants were presented with the instructions of the experiment. These instructions can be found in Appendix A.

After having read the instructions participants were redirected to OSWeb (Mathôt, Schreij & Theeuwes, 2012). Here, they could get acquainted with the task by performing two practice blocks consisting of ten trials each. Feedback was provided during the practice blocks by having the screen turn green if the response was correct or red if the response was incorrect. After practice, the experiment could be started. The experiment consisted out of four blocks of 30 trials, meaning that data was collected on 120 trials in total per participant, and that there were six trials per experimental condition. No feedback was provided for these trials. Participants could take a break between blocks if they so desired. Each block employed only one kind of warning signal, ensuring that the effect of one type of warning signal cannot transfer to a next trial employing a different warning signal. Whether a participant started with a centered or distributed warning signal was determined at random. This was done to ensure that the effects of the warning signal can be attributed to the signals, rather than to a possible primacy effect where responses could systematically deviate in the first block relative to consecutive blocks. Accordingly, two blocks were dedicated to the distributed warning signal and two blocks were dedicated to the centered warning signal.

For the manipulation of attention, warning signals identical to those used in previous studies were chosen (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Seibel, 2018). The warning signals were employed by having them precede the targets for 500 milliseconds (ms). As can be seen in screen 1 (A) in Figure 3, the distributed warning signal consists of five dots surrounded by flankers. The flankers ensured that the outer dots would not receive additional salience in virtue of having no neighbouring symbols. As each dot corresponds to a possible letter position, the participant's attention was hypothesized to be equally distributed across positions. The centered warning signal, on the other hand, consists of two vertical lines: one located above and one located underneath the third letter position, as can be seen in screen 1 (B) in Figure 3. Accordingly, the participant's attention was encouraged to be fixated at the centre position of the (non)words.

Figure 3

Screens Displayed in Each Trial



Note. Visual representation of screens included in each trial of the experiment. "Screen 1 (A)" displays the distributed warning signal, while "Screen 1 (B)" displays the centered warning signal. “Screen 2” displays the presentation of a target. “Screen 3” displays the mask, target position (2) and answer box.

Each trial consisted out of four screens. First, participants were presented with a blank screen for 1000 ms, after which the warning signal would appear for 500 ms. This could either be the distributed or the centered warning signal depending on the block. Consecutively, the target (non)word would appear for 50 ms. The (non)words, too, were surrounded by flankers in order to ensure that letters at P1 and P5 would not receive additional salience relative to letters at P2, P3 and P4. Next, a mask consisting of #@@@@@#, an answer box, and the target position would appear. The mask ensured that participants would not be able visualize an after image of the target on the screen, and the flankers, again, ensured that the outer positions did not receive any additional attention. The flankers themselves did not count as a position which could be retrieved. The mask was fixed until participants had chosen and entered their answer, which was done by selecting an answer on their keyboard (e.g., ‘E’) and pressing enter. Participants were instructed to answer as accurately as possible. This cycle was repeated until all blocks were completed. The total duration of the experiment was approximately 20 minutes. A visual representation of the abovementioned procedure can be found in Figure 3.

After finishing all 120 trials, participants were redirected to Qualtrics to be debriefed. During the debriefing, participants were given information on the background of study, as well as the predicted effects. Participants were provided with a visual representation of their own scores and the expected scores by means of a simple bar chart. After this, the experiment was finished and participants would receive their credits or monetary reward if applicable.

Analysis

The experiment reflects a within-subjects design as each participant is measured on all experimental conditions. Accordingly, the data was analysed by means of a Repeated Measures (RM) ANOVA. Specifically, a three-factor RM ANOVA with factors word-type, position and warning signal was employed in order to estimate the main- and interaction-effects of the independent variables. In addition, four one-way RM ANOVAS with factor position, including pairwise comparisons, were employed for estimating the significance of differences between specific positions in (non)words varying in their level of warning signal and word-type. That is, each of the four one-way RM ANOVAS was applied to a distinct part of the data reflecting one of four possible combinations of these two variables (e.g., centered warning signal and nonword). The datasets were prepared for analysis by following the aggregation and restructuring procedures described by Lacroix and Giguère (2006).

Results

The hypotheses of the present study implied a three-way interaction between word-type, position and warning signal. Most notably, a performance peak at P3 of nonwords cued with the centered warning signal was expected, while nonwords cued with the distributed warning signal were predicted to take on a hook-shaped distribution. Words in both the distributed and centered condition, conversely, were predicted to show no differences between consecutive positions. Mauchly’s test of sphericity confirmed that the assumption of sphericity was not violated. The three-factor RM ANOVA indicated an insignificant three-way interaction between the variables word-type, letter-position and warning signal, $F(4, 180) = .885$, $p = .474$, $\eta_p^2 = .019$. This result can be attributed to an insignificant interaction between word-type and warning signal, $F(1, 45) = .064$, $p = .802$, $\eta_p^2 = .001$. While this does not indicate whether a performance peak at P3 of nonwords cued with the centered warning signal was found, it does disconfirm the prediction that the warning signal has distinct effects on nonwords and words. Pairwise comparisons will be discussed shortly in order to gain more insight into this matter. An overview of the main- and interaction-effects can be found in Table 1. Notably, the interaction effect between word-type and position was significant, $F(4, 180) = 57.856$, $p = .000$, $\eta_p^2 = .562$, which indicates that, as expected, letter-recall accuracies were distinct for the two word-types. While the significant main-effect of the warning signal was implicit in the hypotheses, $F(1, 45) = 9.369$, $p = .004$, $\eta_p^2 = .172$, it should be noted this effect reflects an unexpected finding, whereby performance was generally lower for centered cue trials relative to distributed cue trials.

Table 1

Results of the Three-Factor RM ANOVA

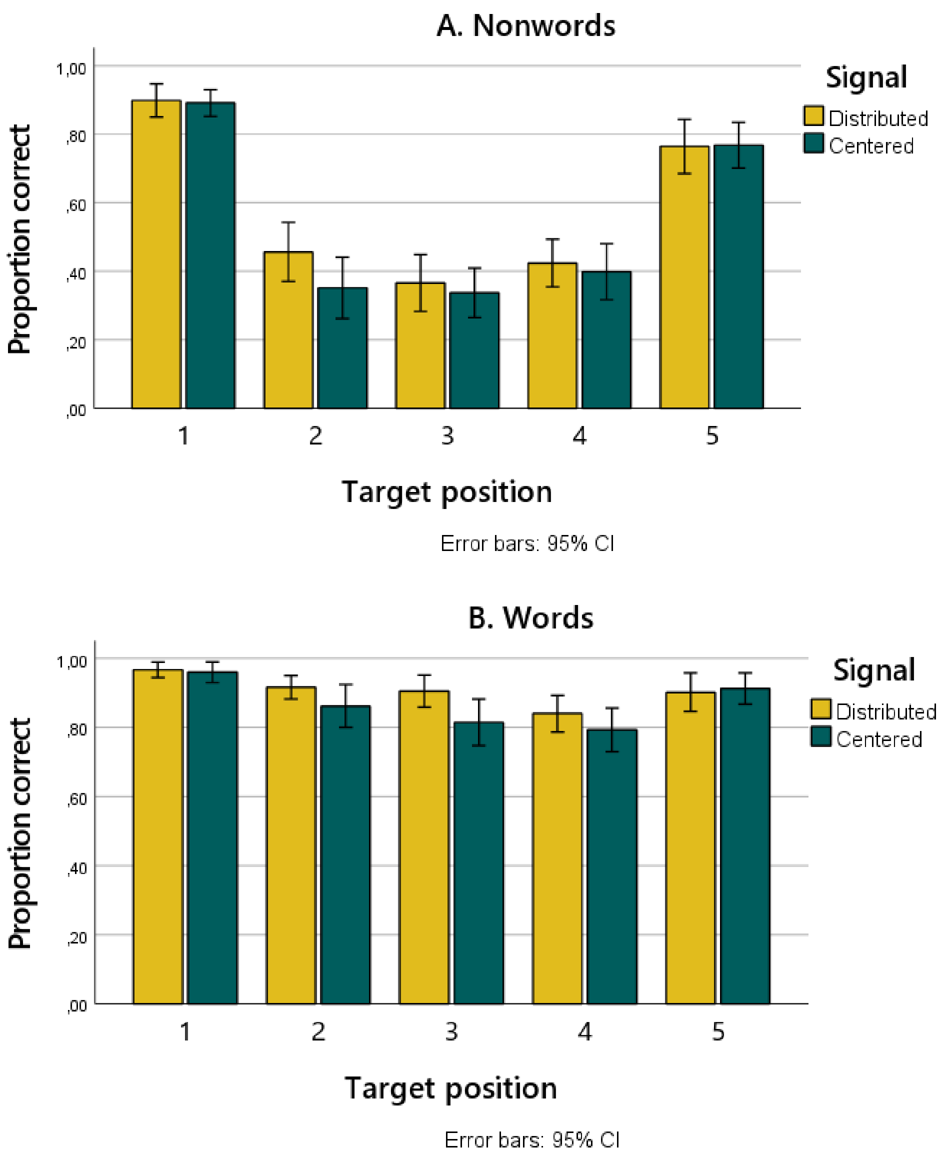
Source	df	F	p	η_p^2
Word-type	1; 45	340,574	,000*	,883
Position	4; 180	100,502	,000*	,691
Warning signal	1; 45	9,369	,004*	,172
Word-type x Position	4; 180	57,856	,000*	,562
Word-type x Warning signal	1; 45	,064	,802	,001
Position x Warning Signal	4; 180	2,660	,034*	,056
Word-type x Position x Warning signal	4; 180	,885	,474	,019

Note. Results of the three-factor RM ANOVA with factors word-type (two levels), position (five levels) and warning signal (two levels). Significant *p*-values are marked (*) with significance level set at ≤ 0.05.

As noted, pairwise comparisons were employed in order to estimate the distribution of letter-recall accuracy across position in the various experimental conditions. A Bonferroni adjustment was applied to this analysis. It was predicted that nonwords preceded by a centered cue would show a relative performance peak at P3. The analysis, however, indicated a U-shaped distribution (see graph A in Figure 4), whereby P2-P4 had no significant differences, $p > .05$, but were all significantly lower than P1 and P5, $p < .05$. To be more specific, the analysis indicated a significant decrease from P1 (M = .891, 95% CI [0.853, 0.930]) to P2 (M = .351, 95% CI [0.264, 0.438]), but no significant difference between P2 and P3 (M = .337, 95% CI [0.267, 0.407]) or between P3 and P4 (M = .399, 95% CI [0.319, 0.478]). P3 and P4 both showed a significant decrease relative to P1, while P5 (M = .768, 95% CI [0.703, 0.834]) showed a significant increase relative to P2, P3 and P4.

Figure 4

Mean Responses Across Experimental Conditions



Note. Graph A represents results for nonwords and graph B represents results for words. The target position is represented along the X-axis, while the Y-axis represents the proportion of correct responses averaged across participants. Yellow bars represent the distributed condition; green bars represent the centered condition.

It was predicted that the nonwords cued with the distributed warning signal would show a hook-shaped distribution. Again, however, pairwise comparisons indicated a U-shaped distribution (see graph A in Figure 4), whereby P2-P4 had no significant differences, $p > .05$, but were all significantly lower than P1 and P5, $p < .05$. To be more exact, pairwise comparisons indicated a significant drop in letter-recall accuracy from P1 (*M* = 899, 95% CI [.851, .946]) to P2 (*M* = .457, 95% CI [.327, .540]) but no further drop from P2 to P3 (*M* = .366, 95% CI [.285, .447]) or from P3 to P4 (*M* = .424, 95% CI [.356, .492]). Unsurprisingly, P3 and P4 were significantly lower than P1. P5 (*M* = .765, 95% CI [.688, .841]), however, showed a significant increase relative to P2, P3 and P4.

The words cued with the centered warning signal were predicted take on higher letter-recall accuracies than the nonwords, with no significant differences between consecutive positions. Analysis of the words preceded by the centered warning signal, however, indicated that these words took on a distribution similar to the nonwords (U-shape), albeit with higher average scores on the DV (see graph B in Figure 4). That is, P2-P4 had no significant differences, $p > .05$, but were all significantly lower than P1 and P5, $p < .05$. To be more precise, pairwise comparisons indicated a significant decrease from P1 (*M* = .960, 95% CI [0.931, 0.989]) to P2 (*M* = .862, 95% CI [.802, .923]) but no significant differences between P2 and P3 (*M* = .815, 95% CI [0.750, 0.880]) or P3 and P4 (*M* = .794, 95% CI [0.732, 0.855]). Resembling the nonwords, both P3 and P4 were significantly lower than P1, while P5 (*MD* = .913, 95% CI [.896, .957]) showed a significant increase relative to P3 and P4.

The words preceded by a distributed warning signal, too, were predicted to have higher letter-recall accuracies than the nonwords, with no significant differences between consecutive positions. Indeed, pairwise comparisons supported this hypothesis; the analysis indicated that there were no significant differences present between any consecutive positions (see graph B in Figure 4), $p < .05$. To be more exact, no significant difference between P1 ($M = .967$, 95% CI [.946, .989]) and P2 ($M = .9167$, 95% CI [.883, .950]), P2 and P3 ($M = .906$, 95% CI [.861, .951]), P3 and P4 ($M = .841$, 95% CI [.789, .892]) or P4 and P5 ($M = .902$, 95% CI [.848, .957]) was indicated by the analysis.

Discussion

The present study tested a set of hypotheses concerning the effects of word-type and warning signal on letter-recall accuracy at specific positions in (non)words. The main prediction was that nonwords, which had a low head-frequency, would show a relative performance peak at P3 when cued with the centered warning signal. This prediction, however, was not supported by the results. In fact, the recall accuracies took on a U-shaped distribution, whereby P2-P4 had no significant differences and were all significantly lower than P1 and P5. This result is inconsistent with previous studies which found a hook-shaped distribution in nonwords cued with a centered warning signal (Donelan, 2018; Freericks, 2018, Seibel, 2018). Nevertheless, the present results are consistent with these studies in that neither found a relative performance peak at P3, indicating that the centered warning signal does not exert its hypothesized effect.

The second prediction was that letter-recall accuracy would take on a hook-shaped distribution across positions in nonwords cued with the distributed warning signal. Indeed, as the effects of attention should be negligible due to even scattering across positions, this hook-shape is implied by the serial binding mechanisms postulated in the conceptual network. This prediction, however, was only partially supported. A significant decrease from P1 to P2 was found, but there was no further significant decrease from P2 to P3 or from P3 to P4. In fact, there were no significant differences between P2-P4, and they were all lower than P1 and P5. Again, the distribution of letter-recall accuracy across positions was U-shaped, rather than the predicted hook-shape. This result is inconsistent with previous experiments which did find a hook-shaped distribution in nonwords cued with a distributed warning signal (Donelan, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019), as well as with studies which found a distribution closely resembling a hook, except in that there was no significant difference between P3 and P4 (Bhouri, 2018; Freericks, 2018; Seibel, 2018). However, the fact that no performance peak at P3 was found – as there was by Buijsman (2019) and Whittaker (2019) – suggests that the performance peak found in these studies may indeed by attributed to the head-frequency of nonwords with target position 3 used in these experiments. Indeed, this is implied by the fact that the present study controlled for the head-frequency of nonwords, while the studies by Buijsman and Whittaker did not.

Words cued with the centered warning signal were expected to elicit no significant differences between consecutive positions. Indeed, the conceptual network suggests that words, especially when recognized, provide strong top-down excitation to their constituent letters, thus resulting in high letter-recall accuracy scores at each target position. The analysis, however, indicated a significant decrease from P1 to P2-P4, no significant differences between P2-P4, and a significant increase from P3 and P4 to P5. The distribution of letter-recall accuracy across position, thus, took on a U-shape similar to those found in the nonwords, albeit with higher accuracies at each position. This finding is inconsistent with previous studies which found no significant differences between consecutive positions in words cued with the centered warning signal (Donelan, 2018; Freericks, 2018; Seibel, 2018). As will be touched upon shortly, this likely has to do with the main-effect of the warning signal.

Words cued with the distributed warning signal, too, were predicted to take on no significant differences between consecutive positions. Indeed, this prediction was supported by the analysis. This finding is consistent with previous studies which found a similar result in words cued with a distributed warning signal (Bhouri, 2018; Donelan, 2018; Mudogo, 2019; Seibel, 2019; Whittaker, 2019) but inconsistent with studies which found significant differences between (at least some) consecutive positions in words (Buijsman, 2019; Pink, 2019; Schwartzkopf, 2019).

As has become clear, the results of the present study are not consistent with some of the postulated hypotheses. Firstly, instead of a hook-shaped distribution in nonwords cued with the distributed warning signal and a relative peak at P3 in nonwords cued with a centered warning signal, both nonwords in the distributed and the centered condition took on a U-shaped distribution. The finding that nonwords cued with the centered warning signal took on a distribution similar to the nonwords cued with the distributed warning signal is not completely unexpected; earlier studies, too, found that distributions in these conditions resembled one another (Donelan, 2018, Freericks, 2018; Seibel, 2018). Furthermore, these studies, too, found no performance peak at P3 in nonwords cued with the centered warning signal. Accordingly, there is strong evidence to suggest that the centered warning signal does not increase performance at the centre position of nonwords and that this is not a language-specific phenomenon. This finding could be explained by the insufficiency of the warning signal – perhaps attention is not, in fact, centered. Alternatively, increased attention at a particular location does not influence strength of binding. More generally, these results support the notion that the performance peak at P3 in Dutch nonwords found by Buijsman (2019) and Whittaker (2019) can, most likely, not be attributed to a disproportionate focus of attention at the centre of nonwords.

Perhaps more surprising is that both the nonwords cued with the distributed and centered warning signal took on a U-shaped distribution. Again, more than one explanation is possible. Firstly, the nature of serial binding and its associated neural decay may have been misconstrued. Accepting the results at face value suggests that serial binding may indeed facilitate position-specific recall but that neural decay occurs much less gradually than hypothesized. That is, neural decay from P1 to P2 induces a steep decrease in performance but no further decrease thereafter. Such an explanation is not unconvincing, as it is plausible that there exists lower limit to the decay process. Previous experiments, however, *did* find hook-shaped distributions in nonwords (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019). This indicates that there might be an alternative, more plausible explanation of the present results. The current study differed from these studies in that nonwords were ensured to have a low head-frequency. The found U-shaped distribution, thus, can be understood if one considers that the tail-frequency (i.e., last three letters) of nonwords may have been high relative to their head-frequencies. Were this the case, then top-down effects induced by high-frequency tails on P1 and P2 could have been negligible in virtue of these positions not being part of the tail, while P3-P5 would have received additional top-down activation from word nodes containing matching letter combinations, thereby inducing an increase in performance at P3, P4 and P5. Indeed, this would explain why there was no further decrease from P2 to P4. Further empirical studies are needed to confirm or falsify this explanation, perhaps by utilizing a n-th letter task which controls for the tail-frequencies, in addition to the head-frequencies, of nonwords.

The analysis of words cued with a distributed warning signal was confirmative of the hypothesis that there would be no significant differences in letter-recall accuracy between consecutive positions. This effect is unsurprising, as it reflects the well-known phenomenon of the word superiority effect (Baron & Thurston, 1973). The results of the words cued with a centered warning signal, however, contradicted the prediction that there would be no differences between consecutive positions. Letter-recall accuracy was higher than in nonwords, but the U-shaped distribution closely resembled their form. Insight into this finding can be obtained by considering the main-effect of the warning signal. As noted, recall accuracy was lower in centered cue conditions as compared to distributed cue conditions. It may have been the case that focusing one's attention on the centre position made it harder to recognize the (non)words as a whole, thereby decreasing accuracy. For nonwords cued with the centered warning signal this would not have changed the overall distribution as accuracies were already suboptimal. Decreased overall performance on words, however, naturally implies a hook-shaped distribution. That is, once the recognition of a word is sufficiently difficult, top-down effects from a word to its constituent letters may not be strong enough to ensure high performance at each position. In such a situation the hook-shaped distribution is once again implied by the effects of neural decay and reverberation.

The fact that there was a U-shaped instead of a hook-shaped distribution in words cued with the centered warning signal, however, may not be given the same explanation as has been given for the nonwords. As discussed, the explanation given for the U-shaped distribution found in nonwords was that the frequency of nonwords' tails may have been high in comparison to their head-frequencies, resulting in increased letter-recall accuracies at P3, P4 and P5. But such an explanation makes little sense when applied to words. Given the fact that only relatively frequent words were included in the experiment, one would be justified in assuming that both the heads and tails of the words occur frequently in their corresponding language. A more plausible explanation is therefore that the centered warning signal may have interfered with the retrieval task by having participants focus on the centre of the words, even though they were simultaneously asked to retrieve a letter at any of the five positions (which requires distributed attention). It is possible that this has distorted the results, but at present this is mere speculation.

As noted, this study was embedded within a larger set of experiments which utilized similar n-th letters tasks. Specifically, a study conducted by Seppälä (2022) reflected the design of the present study with the exclusion that it utilized English, rather than Dutch, (non)words. Results of this experiment largely mirrored the results of the present study: it, too, found a U-shaped distribution in nonwords cued with the centered and distributed warning signal. This provides additional support for the abovementioned conclusions. Results deviated from the present study, however, in that no differences between consecutive positions were found in words cued with *both* the distributed and centered warning signal. While this is inconsistent with the results of words cued with the centered warning signal in the present study, it accords with the initial hypothesis for this condition implied by top-down activation.

Two further experiments utilizing exclusively nonwords with a high head-frequency were largely confirmative of their hypotheses (Bosutar, 2022; Hennink, 2022). That is, a hook-shaped distribution was found for nonwords cued with both the distributed and the centered warning signal. These results can be seen as additional support for the high tail-frequency explanation given for the U-shaped distributions found for the low-frequency nonwords in the current study. Indeed, since the head-frequency of the nonwords in these studies was high, it is unlikely that the tail-frequency would have been high in comparison. The tails of nonwords are thus unlikely to have received more top-down activation than the heads, as might have been the case in the present study. This is further supported by studies conducted by Gontijo-Santos Lima (2022) and Beintema (2022), which found a U-shaped distribution in nonwords with a low head-frequency and a hook-shaped distribution in nonwords with a high head-frequency. In addition, these studies found no differences between consecutive positions of words cued with a centered warning signal, which is inconsistent with the present study's results for words cued with a centered warning signal, but consistent with its initial hypothesis and Seppälä (2022). This indicates that the U-shaped distribution found in words cued with the centered warning signal in the present study should be interpreted with caution.

Some general limitations of the present study are worth mentioning. One limitation was that the experiment could not be conducted in person. The duration of the experiment (and thus number of trials) was reduced because of this fact, as a longer duration was considered unfeasible in a non-controlled environment due to the amount of concentration required to perform the task. An undesirable consequence of this decision is that there were only six trials dedicated to each experimental condition per participant. This is a relatively small number and more trials would otherwise have been desirable. Indeed, more trials per condition would have resulted in greater statistical power and thus more reliable results. Even so, the number of trials was compensated for by a relatively large sample size, so it is not clear whether this should in fact degrade our confidence in the results. A second possible limitation of online experiments is that the environment is not controlled. The appropriateness of the environment – e.g., whether there were no distractors present – can therefore not be guaranteed. Furthermore, even though participants were given the principal investigator's email in case of any questions, it seems reasonable to assume that participants are more likely to ask for clarification if the experimenter is physically present. A final point to note is that nonwords were scrambled such that they were non-existent in the language corresponding to the experiment (i.e., Dutch). It is not ruled out, however, that these 'nonwords' may have been existing words in other languages. Bilingual participants could therefore have perceived some nonwords as words, which could have potentially distorted the results.

Clearly, further research is needed in order to confirm whether the nature of serial binding has been misconstrued, or whether the found U-shaped distributions can be attributed to the tail-frequencies of nonwords. Until then, alternative explanations remain plausible. While results of the present study were not conclusive, strong evidence against the hypothesized effect of the centered warning signal has accumulated (Beintema, 2022; Bosutar, 2022; Donelan, 2018, Freericks, 2018; Gontijo-Santos Lima, 2022; Hennink, 2022; Seibel, 2018; Seppälä, 2022). None of the present or previous studies found a performance peak at P3 of nonwords cued with the centered warning signal. It cannot be ruled, however, that the manipulation itself was insufficient, so further experiments utilizing improved warning signals could be informative. Furthermore, it seems that the relative performance peak at P3 in Dutch nonwords found by Buijsman (2019) and Whittaker (2019) can, indeed, be explained in terms of the head-frequency of the selected nonwords with target position 3. The present study, as well as Beintema (2022), Bosutar (2022), Gontijo-Santos Lima (2022), Hennink (2022) and Seppälä (2022), did not replicate the performance peak at P3. All of these studies, importantly, controlled for the head-frequency of the used nonwords.

Conclusively, the present study supports the notion that position-specific recall of letters is facilitated by serial letter identity-position binding. Indeed, this conclusion is implied by the decrease in letter-recall accuracy following the first position, and the relative increase in letter-recall accuracy found at the last position. Serial binding, thus, remains a plausible solution to the binding problem, but it is by no means confirmed. That is, even though the hypotheses of the present study were derived from theorizing on the structural level, meaning that predictions followed from hypothesized neural mechanisms, the experiment itself was operative at a functional level. Accordingly, the results are consistent with these mechanisms but cannot provide direct evidence for them. A next step in solving the problem of letter position-identity binding, or the binding problem more generally, therefore, lies in neuroscientific research. While future behavioural research on this topic should focus on the role of tail-frequencies in inducing U-shaped distributions in nonwords, neuroscientific research should focus on locating the specific neural mechanisms underlying position-specific recall, so that these mechanisms can be understood with greater confidence and at multiple levels of explanation.

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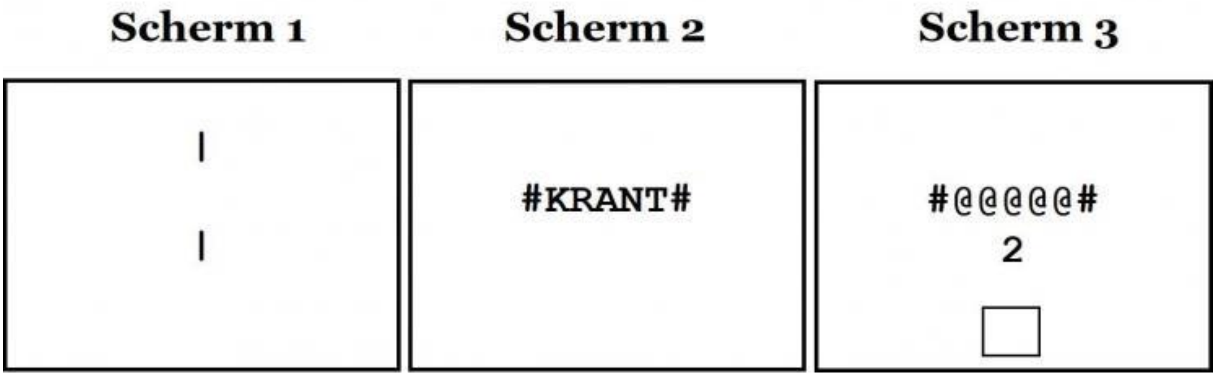
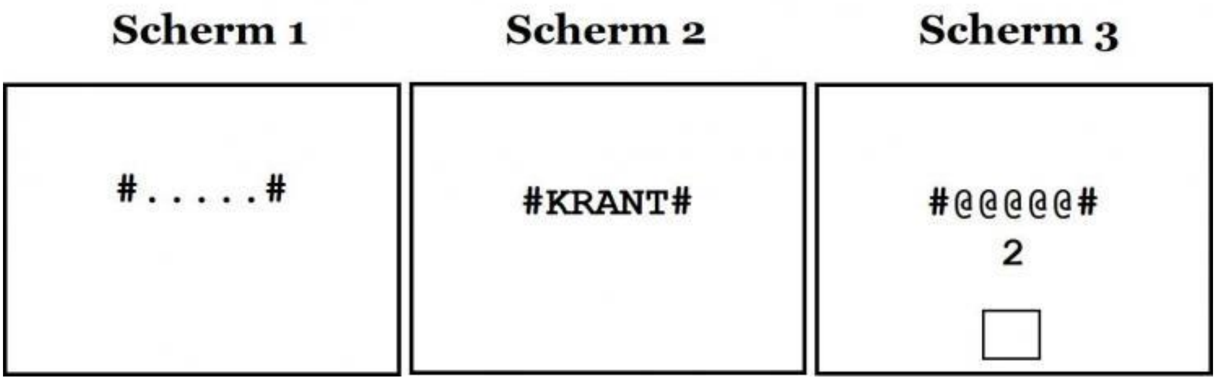
Appendix A

Instructions



Het experiment bestaat uit verschillende opgaven. In elke opgave verschijnen er drie schermen achter elkaar, zoals in het voorbeeld hierboven. De ruimte tussen de twee verticale lijnen in Scherm 1 geeft de middelste positie van de vijf letters aan die zullen worden aangeboden. Scherm 2 laat zien dat deze letters het woord KRANT vormen. In Scherm 3 zijn deze letters gemaskeerd en wordt onder het masker een getal getoond. Jouw taak is om de letter van het aangeboden woord in te typen dat op de positie stond dat is aangegeven door het getal. Voor het tellen van posities spelen de hekjes geen rol. In het voorbeeld geeft positie 2 daarom aan dat de in te typen letter de R is.

Het is ook mogelijk dat een opgave begint met een ander waarschuwingssignaal, zoals weergegeven in de figuur hieronder:



In deze opgaven toont het waarschuwingssignaal de vijf posities van de letters die moeten worden gerapporteerd, ook weer omringd door hekjes. We vragen je om je te concentreren op deze vijf posities.Voor de rest is alles hetzelfde als in het eerste voorbeeld. Ook hier moet je dus de letter R intypen.

Je kan je invoer corrigeren door op de PIJL-LINKS-toets te drukken. De letter die je intypt, verschijnt in het vierkant onderaan het scherm. Om de invoer te bevestigen moet je op de ENTER- of RETURN-toets drukken. Daarna verschijnt dan de volgende opgave. Let goed op, want Scherm 2 wordt steeds maar heel kort aangeboden, slechts 50 milliseconden.

Je bent nu klaar om te beginnen met twee oefenblokken van elk tien opgaven. In deze opgaven zullen de letters in het scherm steeds groen oplichten nadat je een goed antwoord hebt gegeven. Bij een verkeerd antwoord lichten ze op in het rood. Tijdens de opgaven van het experiment zelf zal deze feedback er niet zijn. Voor elk van de vier blokken van dertig opgaven van het experiment, krijg je per blok een melding van je proportie goede antwoorden. Tussen twee blokken kun je even een korte pauze nemen. Is alles duidelijk? Klik dan op --> en we leiden je naar de oefenopgaven. Klik op <-- als je de instructie nog eens wilt lezen.

Tijdens de trainingsopgaven en het experiment kun je je muis niet langer gebruiken. Alle antwoorden moeten dan met het toetsenbord gegeven worden.