Does Head frequency Affect the Process of Letter Recall Based on the Conceptual Model?

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Abstract

This follow-up study builds upon a conceptual network (CN) model and the notion of serial binding in an effort to investigate the effect of head frequency manipulation in word reading. Most previously conducted studies based on this model found a hook-shaped distribution over letter positions in non-words for letter recall accuracy. However, two studies conducted in Dutch non-words found an unexpected peak in position three, contradicting the CN. Head frequency manipulation was hypothesized as an explanation for this peak. The unexpected peak observed in the previous studies was indirectly found in this study. High head frequency was shown to affect letter recall accuracy compared to a head with low frequency. However, the distribution of non-words with High Head-Low Tail frequency did not take the predicted hook shape over positions. An explanation lies in the head frequency manipulation and the top-down processing that words receive in word recognition. Although the study provided supportive evidence toward serial binding and the CN, further research needs to be conducted to confirm the role of head frequencies in word reading and letter recall.

Keywords: Conceptual Network, Serial binding, Letter Recall, High head frequency

Does Head frequency affect the process of letter recall based on the conceptual model?

Reading is a skill individuals develop early in life, usually between 6 to 7 years of age. As literate individuals mature and their brains develop, they progressively become "experts" in reading words with remarkable ease. A single glance is enough for a person to perceive and organize letters into groups of shapes, hence making sense of information. Therefore, despite the ability of humans to scan words, they are also quite skillful in raednig jumbeld wrods wtih appaernt aese (Grainger & Whitney, 2004). All readers of this paper would have no problem reading the previous sentence. Reading the anagrams above requires knowledge of the correct letter position in order to encode the word. This effortless reading of the jumbled sentence suggests a flexible coding scheme of letter positions which has been studied before. For further research of this coding scheme, this follow-up study will be driven by a particular task in word-reading, namely, active letter-recall per position.

The identity and position of a letter within a word constitute two essential properties that aid the process of word recognition and hence word reading. The ability to process these two features simultaneously is termed orthographic processing (Grainger, 2008). Several researchers have attempted to explain how neuronal populations encode and identify letters in relation to their position within a word. Cattel, (1886) was the first to discover the *word superiority effect (WSE)* phenomenon, suggesting that letters presented within a word can be more easily identified than in a non-word (random letter sequence). Reicher, (1969) and Wheeler, (1970) were essential contributors to WSE as they tested Cattel's notion in their research papers and supported it with empirical evidence. A model that first attempted to provide an explanation of the WSE is the *Interactive-activation model (IAM)* (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982).

The IAM is a functional word-processing model suggesting that a letter within a word gets activated through a combination of bottom-up perception and top-down activation. The explanation of the WSE lies in the lack of the top-down activation process when encoding the non-word, which would inevitably lead to non-letter recognition. Despite the explanation the IAM offers, its encoding mechanism makes use of a position-specific slot encoding. This approach is problematic since it codes the absolute letter position instead of the relative position of a letter sequence. This encoding precision would lead to many duplications of letters and hence to an inflexible coding scheme (Grainger, 2008). The jumbled sentence presented earlier in this paper is a phenomenon termed transposition priming. Using this sentence as an example, the proposed theory of IAM would fail to capture this transposition phenomenon. This failure is due to the 50% orthographic overlap the jumbled sentence would have with the original. In consequence, despite the elucidation IAM offers on word recognition, it is unsuccessful in explaining the effects of the active letter recall task that is the focus of this follow-up study.

Open bigrams were proposed as an alternative encoding model that would lead to a higher orthographic overlap. They are a dominant computational mechanism that codes the relative position of letters compared to the encoding of the absolute letter position used in the IAM. This encoding system makes use of ordered letter pairs (i.e., “MAKE: MA, MK, ME, AK, AE, KE”), which renders it relatively insensitive to transpositions since the transported letters have a correct-relative position. A model making use of open bigrams is the SERIOL model (describing the SERIOL model would occupy the available space, however, the whole issue can be found under the reference section) (Whitney, 2001). Despite being biologically plausible, this model too is not suitable for describing the underlying mechanisms involved in active position-specific letter recall.

The abovementioned models offered a general understanding of well-established findings (i.e., WSE, Open bigrams) involved in word-reading and letter recognition mechanisms. Nonetheless, models described at the functional level fail to explain the biological plausibility of word-reading mechanisms. This implies that the reverse process of WSE (from words to specific letter positions) constitutes a challenge to such word-processing models (Baron & Thurston, 1973). In order to study these mechanisms, one should focus on the structural level of description, where position-specific top-down activation from the word to the letter must exist (de Vries, 2016).

The Conceptual Network

The conceptual network proposed by de Vries, (2016) is a biologically plausible word-processing model that builds on the limitations of the previously proposed models. This thesis and the empirical research used as supporting evidence are based upon this cognitive model. The conceptual network is organized in cell-assemblies. A cell assembly is a cluster of neurons stronger interconnected compared to their connections with the surrounding neurons, and each represents a memory trace. The basis of this model is upon self-organization principles, meaning that the functions of the cognitive system are a product of the interactions between the neuronal populations within it. Moreover, the model assumes a neural binding of representations since it views their identity and location separately represented within the system. In this way, temporary combinations of neural representations of letters, locations and positions can be distinguished during word processing and avoid the increased number of memory traces that would be caused due to neurological interference– superposition catastrophe (von der Malsburg, 1981) or the position-specific encoding used in IAM.

The organization of the conceptual network has its foundation in the Tanzi-Hebb learning rule. This rule states that pairs of neurons receiving simultaneous coincidental activation increase in connectivity (Hebb, 1949). These different connections between the cell assemblies form a neural network. However, the connections between the neurons are not permanent but instead temporary and situation-specific. The model suggests a subnetwork that actives the cell assemblies that represent a memory trace for a specific context. In de Vries (2016), the phenomenon of spike-resonance is stated as follows: “At the structural level, this activation ensures that the spike trains produced by the neurons of the interconnected assemblies are *in phase*”. (p. 23). At the functional level, a cell assembly that becomes activated below the threshold level represents a memory trace at a priming phase. On the other hand, the cell assembly that surpasses the critical threshold represents a memory trace that is in working memory. Therefore, for word recognition, the cell assemblies that correspond to the memory traces of the letter nodes need to become activated at a level that surpasses the critical threshold.

The conceptual network

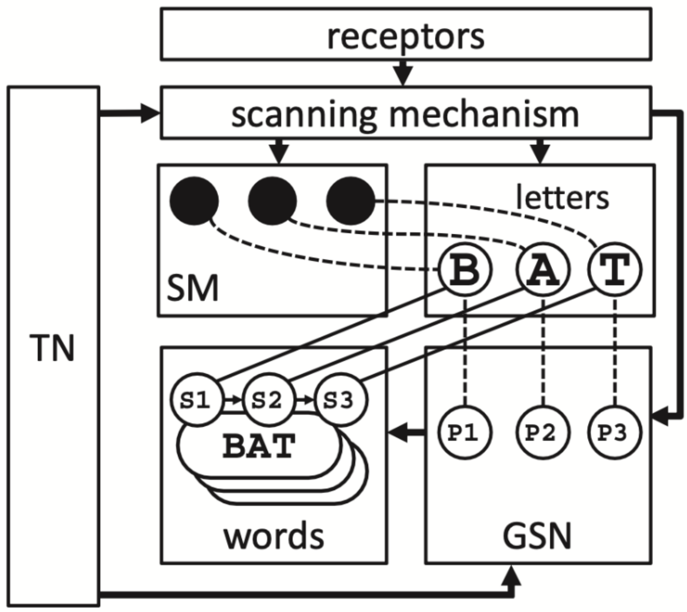


Figure 1. A visual representation of the conceptual network for word and letter recognition. The model consists of a spatial map (SM), word and letter subnetworks, the global sequence network (GSN), and the task network (TN). The dashed lines represent a temporary connection (binding), whereas the solid lines represent module activation by means of

permanent connections. Image retrieval from de Vries, P.H. (2016). Neural binding in letter and word recognition. In K. E. Twomey, A. Smith, G. Westermann, & Padraic Monaghan (Eds.), *Progress in neural processing. Neurocomputational Models of Cognitive Development and Processing* (pp. 17–33). World Scientific Publishing.

The conceptual model assumes that binding between its subnetworks occurs serially. Two neural excitations take place for a single letter, namely for their location and identity. Consequently, a word that consists of multiple letters that receive simultaneous activations would lead to an interference in spike-resonance if the binding was parallel instead of serial. The CN proposes that a scanning mechanism within the network scans the letters from left to right, transforming them into excitation pairs. Subsequently, this mechanism serially releases the pairs into the network, meaning one triggering the next one, where a simultaneous activation for their location and identity takes place (de Vries, 2016). As letter nodes become serially activated, the phenomenon of letter decay is observed, known as the *letter decay effect* (de Vries, 2020). In particular, the first letter node receives the greatest activation while each consecutive letter node gets serially activated in a declining manner. Reaching the last letter node, the activation of neurons reverberates at the same letter since there is no subsequent letter node to become activated. This phenomenon is known as *the reverberation effect*. Consequently, the temporary connections of the last and first letter nodes will be stronger, hence having a superior letter recall compared to the middle positions. The distribution of these letter nodes over positions would resemble a hook, with the first letter node having the strongest temporary connection.

The example above applies to non-words which requires a coding process from letters to words. However, what applies to words is also a reverse process, namely, a serial coding process from words to letters. In this case, word nodes influence the activation in the network by using both top-down and bottom-up processes. In consequence, their letter recall is relatively faster and more accurate in comparison to non-words owing to the significant role that memory plays.

Previous Studies

A series of studies were conducted using the CN model as a foundation to test the abovementioned effect. The experiments were conducted in three different languages, Dutch, English, and German, employing an active letter-recall task using five-letter words and non-words. The researchers hypothesized that (a) words would have a higher letter recall accuracy than non-words, (b) there would be a decrease in recall accuracy from the letter positions 1 to 4, and (c) the fifth position will have higher recall accuracy due to the reverberation effect and (d) the letter recall accuracy for consecutive positions in words will be better compared to the non-words. Researchers received supportive evidence for the hypotheses (a), (c) and (d). Therefore, there is supportive evidence that since words receive more robust top-down activation than non-words, their letter recall accuracy was higher. Moreover, findings were in line with the reverberation effect phenomenon as there was an activation spike in the fifth letter position. Nonetheless, researchers observed a neural spike in the third position of Dutch non-words, which contrasts with their third hypothesis. However, the same effect was not observed in the German and English non-words. This finding could be attributed to a disproportionately increased attention to the middle letter of the Dutch non-word letter sequences (Buijsman, 2019; Mudogo, 2019; Pink, 2019; Schwartzkopf, 2019; Whittaker, 2019).

In order to test this phenomenon, a second series of studies were conducted to derive insight into the role of attention in all three languages. These studies followed a similar active letter recall task experiment but with an addition of attention manipulation in both words and non-words. Researchers used a warning signal which was either centered or distributed. Centered warning signals directed participants' attention in the center position, whereas the distributed warning signals aimed to distribute attention equally across all letter positions. Researchers hypothesized that both warning signals would not affect the words due to the top-down activation they receive. Additionally, distributed warning signals were expected not to affect the non-words. Both hypotheses were supported by statistical evidence. Nonetheless, researchers had predicted that using a centered warning signal would result in an increased activation in the third letter position. Results provided evidence against this hypothesis since no effect was observed in all languages. Therefore, the distribution resembled a similar hook-shaped pattern over positions observed in previously conducted studies (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Seibel, 2018). This paper will refer to both series of previous studies as Base Studies.

Observing the findings collected from the Base Studies on this topic, there is concrete experimental evidence for the hook-shaped pattern over positions for both words and non-words. The performance peak observed in the third position of Dutch non-words could be due to a high head (HH) frequency, meaning a letter combination frequently encountered in words. A hypothesis resulting from visual inspection of the stimuli is that the head frequency would be important in influencing the active letter recall of the consecutive letter positions. This hypothesis will drive the purpose of this paper. The present study will focus on English words and non-words with a HH frequency and a low tail (LT) frequency. LT frequency refers to the last three letters of a letter sequence that do not form a common word ending. A HH would create strong temporary connections between the first three letters, facilitating letter recognition and recall. Activation of letter nodes following the third position would have weaker temporary connections since the excitation pairs will have fewer simultaneous activations during the scanning process. It is hypothesized that (a) non-words will have a hook-shaped pattern over positions. However, non-words with LH-LT frequency will have a steeper decline in letter recall accuracy in the first three letter positions compared to those with HH-LT frequency. In addition, non-words with HH-LT frequency will have a higher and gradually declining letter recall accuracy across the first three positions in comparison to the LH-LT frequency condition. Moreover, (b) letter recall accuracy in words is expected to be higher across all letter positions than in non-words. Finally, (c) words are expected to have a flat distribution for both LH-LT and HH-LT conditions.

The present study is part of a series of studies that will manipulate non-words, creating HH-LT and LH-HT letter frequencies, respectively, in Dutch, German and English. This series of studies will provide an extensive experimental test of the unmet hypotheses of the previous studies. It will attempt to elucidate the underlying mechanisms involved in word processing with the assumption of a non-permanent position-specific encoding scheme. Therefore, provide a biologically plausible explanation of how people scan and make sense of jumbled words with this apparent ease.

Method

Participants

The sample used was gathered by means of the online platform Prolific (Palan & Schitter, 2018). The participants' group comprised 46 participants (M_{age} = 24.15, SD_{age} = 3.46) who received a £2 reward. Participation in the experiment was voluntary, and all participants signed informed consent prior to it. The present study focused on English words and non-words. The percentage of participants who were native speakers was 100%. The total sample size used, comprised 60.9 % female participants with (M_{age} = 24.33, SD_{age} = 3.50, age-range 19-30). The study was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences, Department of Psychology, at the University of Groningen.

Design

The present experiment was set up in the format of a 2x2x5 design with three independent variables: word type (two levels: words and non-words), frequency (two levels:

Low Head (LH)-Low Tail (LT) and High Head (HH)-Low Tail (LT)), and letter position (five levels: for each of the five letters in a five-letter sequence). In total, these variables amounted to 20 conditions. The dependent variable was the mean letter recall accuracy. This is given by a proportion of correctly recalled letters in the performance trials.

Stimuli

The study made use of paired words retrieved from the CELEX Centre for Lexical Information (2001) database. Each word pair differed in one letter in one position (e.g., the letter "B" in the word BEACH was replaced by the letter "T" for TEACH; hence creating two different words). The position where the letter in a pair varied was also the target position the participant had to remember. This was done to account for the *word substitution effect* (Reicher, 1969). Participants could potentially guess the target letter by just the surrounding letters; hence the word pair creates ambiguity for which is the correct letter. Therefore, what becomes more important is the target letter and not its surroundings.

The non-words used in the experiment were constructed by rearranging the letters of the corresponding word in a manner to have a HH, LH and a LT frequency. Common words in this context are defined as having a word frequency of >7 per million words. Additionally, the rearrangement of the letters of the corresponding word was done to preserve similar letter frequency levels among the words and non-words, hence maintaining similar physical properties. Consequently, changes in letter accuracy could be attributed to a letter position and not to the physical properties or the frequency of a letter. Keeping target letters in their correct position when creating the non-words was not feasible. The list of non-words constructed consisted of 24 pairs per letter position, excluding the training trials. Due to the increased number of non-words, the experiment would be relatively lengthy, which is not feasible when conducting an online experiment. Therefore, considering that non-words were organized in pairs, using Microsoft Excel, we created two sets of non-words to split the pairs (i.e., first non-word in set 1, second in set 2). For each letter position, each participant was presented with six non-words with LH-LT frequency and six non-words with HH-LT frequency. The same separation procedure was followed for the words of the experiment as they also appeared in pairs.

The Base Studies previously mentioned kept the target letter in the same position in both words and non-words. This main difference between our studies was made to manipulate the letter frequencies and create the conditions HH-LT and LH-LT. Maintaining target letters in the same position would create complications for constructing the optimal head and tail frequencies for non-words.

Procedure

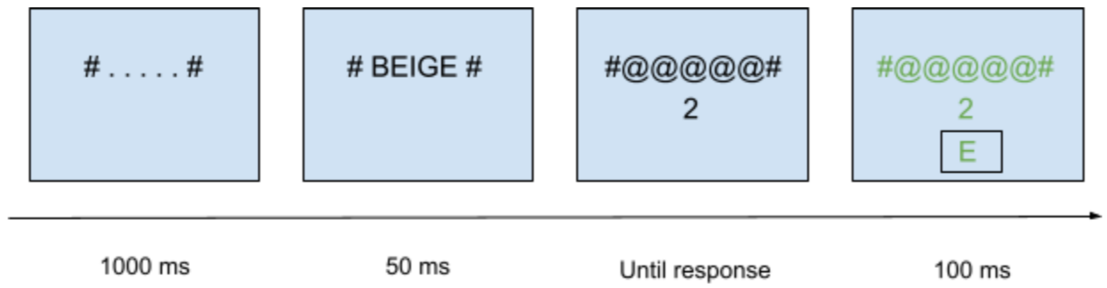
Before the experiment started, participants gave their informed consent upon receiving information about their rights and the nature of the research by means of the online platform Qualtrics (Qualtrics, Provo, UT). They were informed that their age, gender, and performance would be collected and that they could contact the principal investigator via mail should there be any questions. The participants received instructions about the task they would perform after they signed the consent form. The experiment itself was completed online. Participants were instructed to conduct the experiment in a quiet environment without distractions and use a laptop or PC. The experiment consisted of two blocks with ten practice trials in order to familiarize participants with the task. Feedback was given after each reported word. The stimuli in all trials were presented centrally on the computer screen, in the font size of 24p. The chosen font size was increased by 6p compared to the Base Studies, which used a Courier New font of 18 pt. The font size increase was implemented because the previous experiments were carried out on laboratory desktop computers with a display of 27’’ and a resolution of 1920x1080 (Buijsman, 2019; Mudogo, 2019; Pink, 2019; Schwartzkopf, 2019; Whittaker, 2019).

In each trial, four stages followed each other (see Figure 1). The first screen participants were presented with was blank. After 1000ms, a preparation signal ("#.... #”) appeared on the screen, which lasted for 500ms. The preparation signal indicated where the letters of the word would appear. After the preparation signal, the real target appeared for 50ms (e.g., “#WATCH#”). Finally, a mask (#@@@@@#) replaced the target. Bellow the mask, a number between 1 to 5 was presented, representing the number of the letter position to be reported. A visual representation can be found in Figure 1. The last screen remained until the participant filled in a letter and pressed enter. In all situations, the dots, the letters and the ‘@’ were surrounded by ‘#’. This was done to assure consistency on every screen since our visual processing is susceptible to contrasts (see Figure 1). In particular, the first and last letter’s salience (e.g., in the word BEACH, “B” and “H”) would be too prominent and would have an unwanted advantage in contrast to the middle letter positions. Consequently, this results in higher letter recall accuracy for positions 1 and 5. Nevertheless, as we are interested in the relationship of serial binding, we add symbols around the first and last letter positions to accurately test their recall according to the CN.

The software employed to conduct the online study was OSWeb version 1.4.4 and OpenSesame version 3.1 (Mathôt, S & March, J., 2012). The experiment included two training blocks and three experimental blocks. Each training block consisted of ten trials where participants received feedback for the reported letter. When a letter was correctly reported, the word turned green, whereas the word turned red when wrong (see Figure 1). This way, participants could familiarize themselves with the task and get the highest score possible in the experimental block. After each training block, the participant received general feedback in percentages which reflected the accuracy of the recollection of the letters. The experimental blocks consisted of 30 trials each and included only general feedback at the end of a block. In total, each participant was presented with 120 words.

Figure 1.

An example of the sequence of screens in a training block with a correct answer.



Analysis

All data were analyzed in SPSS (IBM Corp., Armonk, N.Y., USA). Raw data were initially aggregated and then restructured. Participants were tested for all experimental conditions; hence, the experiment used a within-subjects design. On account of the within-subjects nature of the experiment, a repeated measures (RM) ANOVA was used for the data analysis. As mentioned in the design section of this paper, the three independent variables used were word type, letter position and frequency. The RM ANOVA examined the main and interaction effects of the independent variables. Four more one-way RM ANOVA were employed in order to examine the effect of head frequency manipulation over positions for both frequency conditions, namely HH-LT and LH-LT in words and non-words. Through these four analyses, we could inspect for decreases in letter recall accuracy over positions in the non-word LH-LT condition and increases in the HH-LT condition due to our manipulation. Therefore, to inspect for a hook-shaped pattern over positions and the effect of head frequency manipulation on letter recall. To get a more detailed image, pairwise comparisons were employed to compare the five letter positions of both words and non-words.

Results

To test this study's postulated hypotheses, a three-way RM ANOVA was conducted with word type, frequency and position factors. The Mauchly's Test of Sphericity in the three-way RM ANOVA indicated a violation of the sphericity assumption for the variables Frequency*Position ($p < 0.008$) and Position*WordType ($p < 0.003$). For the correction of the statistic, the epsilon (ε) Greenhouse-Geisser (GG) correction was employed since epsilon (ε) is greater than < .75. Using Q-Q plots, we checked for the normality assumption that was not violated, and no outliers were present. The p-values in the three-way RM ANOVA were significant across all variables and their respective interaction effects. An overview of this analysis can be found in Table 1.

Table 1.

Overview of the three-way RM ANOVA analysis

Source	df	*F*	*p*	η_p^2
Frequency	1.000*; 45.000*	53.631*	.000*	.544*
Position	3.666*; 164.961*	76.965*	.000*	.631*
WordType	1; 45	324.54	.000	.878
Frequency*Position	3.141*; 141.331*	11.087*	.000*	.198*
Frequency*WordType	1; 45	65.200	.000	.592
Position*WordType	3.280*; 147.590*	32.049*	.000*	.416*
Frequency*Position*WordType	4; 180	41.565	.000	.480

Note. *Greenhouse-Geisser (GG) correction

Note. Alpha set to ≤ 0.05

The most important interaction effect for this study is the three-way interaction between frequency, position, and word type. As shown in Table 1., the three-way interaction's significance is necessary to support the postulated hypotheses; notwithstanding, it is insufficient. Therefore, pairwise comparisons with a Bonferroni correction were employed further to investigate letter recall accuracy between all five letter positions. The variables Frequency and WordType had significant differences (*p* = 0.00), however the variable Position had insignificant differences for positions (P) P5-P3 (*p* = 1.00) respectively. Furthermore, we conducted four one-way RM ANOVA and pairwise comparisons with a Bonferroni correction for non-words and words in both HH-LT and LH-LT letter frequency levels.

Non-words

With respect to the HH-LT non-words, Mauchly's test of sphericity indicated no violation of this assumption. RM ANOVA showed significant results (*F* (4,180) = 52.204, *p* = 0.00, η_p^2 = 0.537). Pairwise comparisons showed significant differences in most letter positions whereby exemptions were the positions P2-P3 and P5-P4 (*p* = 1.00) respectively. Precisely, a slight gradual drop was observed from P1 (*M*= 0.848, 95% CI= [0.781, 0.910]) to P2 (*M*= 0.728, 95% CI= [0.652, 0.804]). From P2 there was a further gradual drop to P3 (*M*= 0.692, 95% CI= [0.615, 0.769]). Subsequently, from P3 the output indicates a steep drop to P4 (*M*= 0.373, 95% CI= [0.308, 0.439]). Finally, from P4 there is a slight increase to P5 (*M*= 0.413, 95% CI= [0.331, 0.495]). Therefore, the distribution of this condition does not resemble the initially predicted hook-shape since there is not a significant increase in letter recall accuracy from P4 to P5. A visual representation of the distribution can be found in Figure 2a.

For non-words with LH-LT letter frequency, the Mauchly's test of sphericity indicated again no violation of this assumption. One-way RM ANOVA showed significant results (*F* (4,180) = 68.295, *p* = .00, η_p^2 = .603). Pairwise comparisons indicated insignificant differences for P2-P5 (*p* = .394), P5-P2 (*p* = .394), P3-P4 (*p* = 1.00) and P4-P3 (*p* = 1.00). However, all other pairwise comparisons reported significant differences and p-values with multiple having (*p* = 0.00). Precisely, a steep drop was observed from P1 (*M* = .822, 95% CI

= [.763, .882]) to P2 (*M*=.391, 95% CI = [.314, .469]). A further gradual drop is observed from P2 to P3 (*M* = .228, 95% CI = [.174, .283]). From P3 to P4 (*M* = .257, 95% CI = [.198, .316]) there is a slight increase in the letter recall accuracy followed by a greater increase from P4 to P5 (*M* = .496, 95% CI = [.413, .580]). This distribution resembles a hook-like shaped distribution that was initially predicted and is visually represented in Figure 2a.

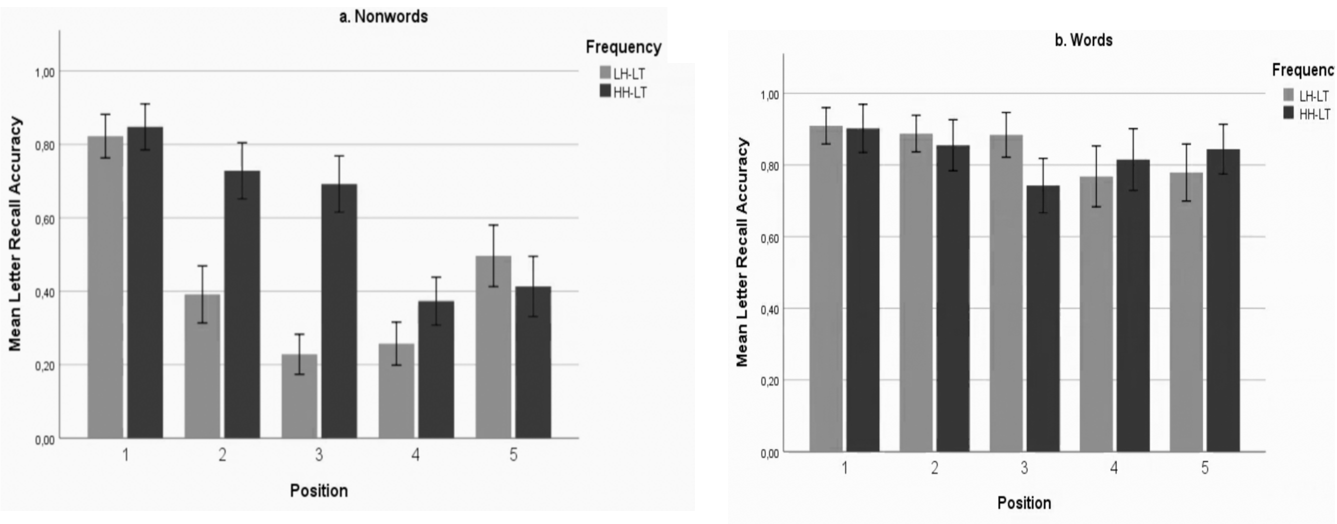
Words

For words with a HH-LT letter frequency, the Mauchly's test of sphericity indicated a violation of the assumption of sphericity (p = .006). The correction of Greenhouse-Geisser (GG) was used. The one-way RM ANOVA indicated significant results (F (3.207, 144.309) = 7.297, p = .00, η_p^2 = .140). Pairwise comparisons showed no significant differences between most letter positions with the highest p-value being (p = 1.00). Exemptions with significant p-values were P1-P3 (p = 0.00) and P2-P3 (p = 0.028) respectively. Precisely, a slight drop in letter recall accuracy is observed from P1 (*M* = 0.902, 95% CI = [.835, .969]) to P2 (*M* = .855, 95% CI = [.784, .926]). A further minimal drop is observed from P2 to P3 (*M* = .743, 95% CI = [.667, .819]); however, from P3 to P4 (*M* = .815, 95% CI = [.729, .901]) a gradual increase is observed in letter recall accuracy. Finally, from P4 to P5 (*M* = .844, 95% CI = [.775, .914]) there is a further increase. The distribution of words in the HH-LT condition does show significant differences in letter recall accuracy across positions P1 to P3 and P3 to P5. Therefore, it does not support the initial prediction that no differences will be observed across the different positions. The distribution can be found in Figure 2b.

For words with LH-LT letter frequency, the Mauchly's test of sphericity indicated a violation of the assumption of sphericity (p = .00), hence the Greenhouse-Geisser (GG) correction was used. The one-way RM ANOVA showed significant results (F (2.674, 120.338), p = .00, η_p^2 = .198). Pairwise comparisons indicated no significant differences between P1-P2, P1-P3, P2-P3 and P4-P5 (p = 1.00) respectively. Significant p-values were found for the rest of the positions with the lowest p-value being (p = 0.00) and the highest (p = 0.045). Precisely, a minimal drop is observed across positions one to four with P1 (M = .909, 95% CI = [.859, .960]), P2 (M = .888, 95% CI = [.837, .939]), P3 (M = .884, 95% CI = [.822, .947]) and P4 (M = .768, 95% CI = [.683, .853]). From P4 to P5 a slight increase in letter recall accuracy is observed with P5 (M = .779, 95% CI = [.699, .858]). In contrast with our initial prediction differences were observed in letter recall accuracy between P3-P4 and P4-P5. A visual representation of the distribution can be found in Figure 2b.

Figure 2.

Mean Letter Recall Accuracy across letter positions of both experimental conditions



Note. Graph a. represents the experimental condition “Non-words" and graph b. the experimental condition "Words". Both graphs contain the five target letter positions on the X-axis and the mean letter recall accuracy on the Y-axis. Light grey bars represent the Low Head-Low Tail (LH-LT) condition, whereas black bars represent the High Head-Low Tail (HH-LT) condition. The error bars stand for a 95% confidence interval around the mean.

Concluding, on the basis of the patterns of the means of the four pairwise comparisons, we observe that the independent variables word type, frequency and position had a greater effect on letter recall accuracy in non-words than words. The significant p-values in the three-way RM ANOVA indicate a three-way interaction effect supporting the prediction of a hook-shaped pattern over positions for non-words and a generally equal distribution of letter recall accuracy over positions but with slight exceptions for words.

Discussion

The present study having as its basis the CN model explained in this paper, hypothesized that non-words in both LH-LT and HH-LT conditions would have a distribution that would resemble a hook shape over letter positions. In addition, the distribution of the non-words with LH-LT frequency was predicted to have a steeper decrease in letter recall accuracy compared to the HH-LT condition, which was expected to have a more gradual decrease across the five letter positions. The results supported the predictions made for the LH-LT condition. The distribution of this condition does resemble the predicted hook shape as from P1 to P3, the distribution steeply decreases, and from P3 to P5, there is a significant increase in letter recall accuracy. P3 is the lowest point of the distribution, hence is in line with the letter decay phenomenon occurring during the serial binding proposed by our model. Lastly, the peak in P5 is explained by the reverberation phenomenon observed in the Base Studies discussed in the introduction section.

Despite the supporting evidence the LH-LT condition received, results were not entirely in accordance with the postulated hypothesis for the HH-LT condition. The distribution for this condition was predicted to have the shape of a hook over positions with a gradual decrease in letter recall accuracy across the first three letter positions. Supporting evidence was found for the gradual decrease in letter recall accuracy due to the HH manipulation. However, the distribution did not take the predicted shape as P5 is not significantly higher than P4 despite the reverberation effect in P5. A plausible explanation of this finding could be the letter frequency manipulation that led to a non-word with a HH. In particular, this manipulation resulted in the non-word resembling a word. According to the

CN model, words have a higher letter recall accuracy due to the top-down activation process. Therefore, serially scanning the first three letters would activate words that begin with this letter combination. Consequently, since there is a top-down activation for word recognition, participants could have reported the letter corresponding to the activated word and not to the actual letter presented. Therefore, leading to decreased letter recall accuracy and a distribution over positions that does not resemble the predicted hook shape.

Our hypothesis for words was that there would be no difference in letter recall accuracy between the two conditions across the five letter positions; hence both distributions will resemble a flat line. Moreover, the words' general letter recall accuracy was predicted to be higher than the one observed in non-words due to the top-down activation process in word reading and the word superiority effect. Our findings were in line with the second part of this hypothesis as a generally increased letter recall accuracy was observed across positions in the condition for words compared to non-words, hence supporting the top-down excitation that letters receive when a word becomes recognized. Nonetheless, the postulated hypothesis for a similar letter recall accuracy across the five positions did not receive support from our findings. In particular, in the HH-LT condition, there is a drop in letter recall accuracy from P1-P3 and then an increase from P3-P5. Similarly, in the condition LH-LT, we observe a drop from P3-P5. This finding explains that the head of words is more dominant in the process of word reading. We scan words from left to right; therefore, the top-down excitation and neural binding the first three letters receive is greater; thus, the letter recall accuracy.

Unexpected Peak in Previous Studies

As mentioned at the beginning of this paper, a performance peak was observed in the third position for Dutch non-words in two of the Base Studies (Whittaker & Buijsman, 2019). Therefore, the distribution of non-words resembled a W-pattern. This follow-up study showed indirect evidence for this peak. Our findings suggest that a plausible explanation for this letter recall peak lies in the head frequency manipulation. Upon visual inspection of the data, a letter position of particular importance is P2 for non-words. Manipulating the letter frequency in P2 for a LH-LT frequency, we observe a significant drop in letter recall accuracy compared to non-words with high head frequency. The same is applied to P4. Most remarkably, letter recall accuracy in P2 with LH-LT is lower than in P3 with HH-LT. Both Base Studies did not account for the head and tail frequency of the non-words presented to the participants. Consequently, including many non-words with LH frequency in P2 and P4 and many non-words with HH frequency in P3 could create the W-pattern over positions previously found. A way to test this alternative hypothesis would be to retrieve the non-words presented to the participants of these two Base Studies and examine their head and tail frequencies.

Other Experimental Designs

A series of similar studies were conducted parallel to the one discussed in this paper. These studies focused on manipulating the non-words' tail frequency, creating a LH-HT and a LH-LT letter frequency condition. Their first hypothesis was that words would have no difference in letter recall accuracy across the five sequential positions. In accordance with our results, their experimental findings did not support this hypothesis. Moreover, it was hypothesized that the distributions over positions of non-words with a LH-HT and LH-HT frequency would resemble a hook shape. Findings supported this hypothesis for the LH-LT condition, reaching a consensus with our findings. Nonetheless, the hypothesis was not supported for the LH-HT condition, which was the case in the present study.

Additionally, they expected non-words with LH-HT frequency to have a higher letter recall performance in the last three letter positions than in the LH-LT frequency condition. Both studies showed that head frequency manipulation led to an increase in letter recall performance when compared to the LH-LT condition. However, only one study showed a gradual increase in letter recall accuracy across the three last positions, whereas the other study's distribution resembled a U-shape. Comparing all the studies conducted for both conditions, we conclude that heads are more dominant compared to the tails of the words since studies that focused on HH-LT showed overall a gradually decreasing letter recall accuracy across the first positions (Kabil, 2022; van der Wal, 2022; Schoell, 2022; Yu, 2022).

Limitations

Despite the largely confirmed hypotheses of the present study, there are a few shortcomings when considering the validity of our findings. Firstly, the study's sample size was small since only 46 participants were tested for the HH-LT condition. Furthermore, participants were presented with lists of six words and six non-words in the twenty conditions of the experiment. The number of words and non-words presented is small; however, considering there were 120 trials, increasing the number of stimuli in the lists would create a lengthy experiment that is not feasible when conducted online. Moreover, the online nature of the experiment comes with certain limitations. Specifically, despite the elaborate instructions provided, participants could have had questions regarding the procedure. The possibility of posing questions was possible but with no immediate response as it would in a laboratory. In addition, although the letter font size was increased, participants' screens and resolution may differ, leading to inconsistencies in the experiment's instrumentation. The general caveats that come with online experiments could be surpassed by replicating the study in a laboratory environment.

Lastly, no background information regarding dyslexia and ADHD was collected. Considering that the experiment demands an increased level of attention as well as the spelling of words, participants with these conditions could negatively influence the results, resulting in less reliable data. Future studies should take into consideration these individual differences since the aim is to discover the underlying processes of word reading.

Conclusion and Implications

Concluding, our hypotheses were, to a large extent, supported by our findings. The CN's proposition of serial binding was supported by the decline in letter recall accuracy in each consecutive letter position and was accompanied by a relative increase in the last position due to the reverberation phenomenon. Frequency manipulation did show an effect on letter recall, explaining the non-hook-shaped distribution over positions of the HH-LT condition. Empirical evidence supporting the CN proposed in this paper can contribute to explaining the underlying processes of word reading. Knowledge about the process of reading can be helpful in many areas. An example could be to better understand disorders such as dyslexia and potentially facilitate the diagnosis and treatment process, such as developing more effective specific teaching approaches to improve peoples' reading skills. Conducting a follow-up series of this study could focus on excluding participants with either ADHD or dyslexia as this could be a confounding variable with a significant impact and conduct the study in a laboratory.

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