The Impact of Tail Frequencies on Position-Specific Letter Recall in (Non)Words

L. M. Schoell

University of Groningen

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P.H. de Vries

In collaboration with: M. Kabil, M. Malea, Y. van der Wal, R. Yu

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Abstract

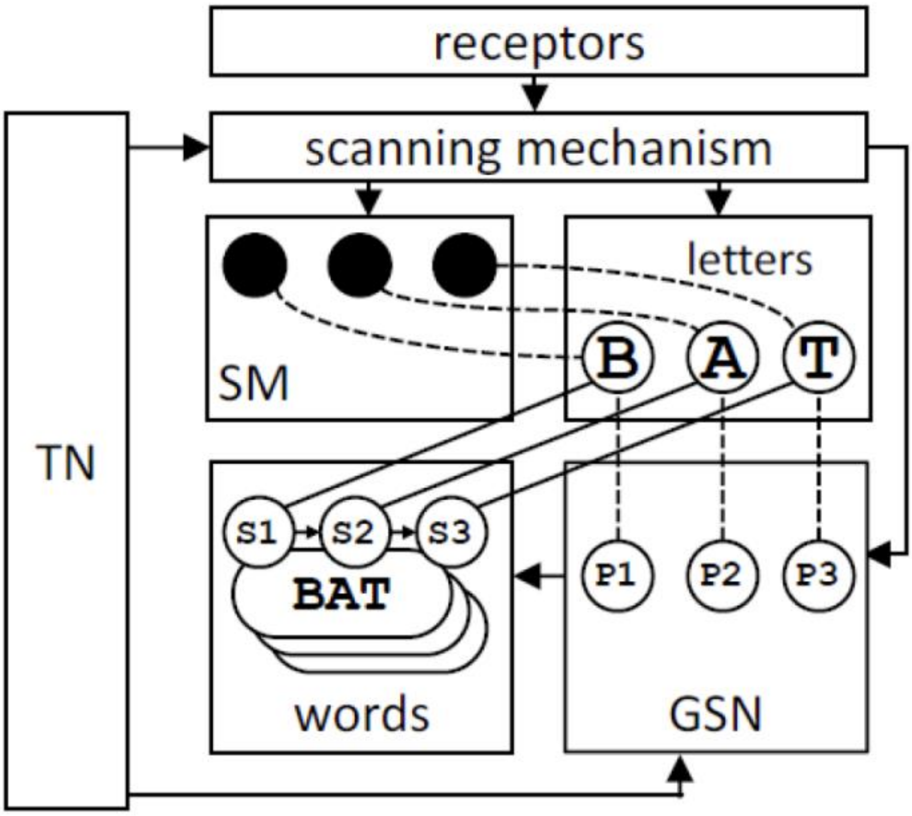
This study is a follow-up to a series of studies exploring the role of letter recognition within the conceptual network model. To investigate this, a task was used to compare words and non-words regarding their position-specific recall performance. Previous results showed an unexpected peak in the third letter position that the model does not account for. We replicated the initial study design and added beginning and end frequency as a control variable as a possible explanation for the earlier results. The last 3 letters were designed so there would be either many or hardly any (non)words starting/ending with this word string. Results showed an unexpected significant 3-way interaction effect between word type, letter position, and frequency, with significant results for positions 3, 4, and 5. Higher frequency non-words had higher recall accuracy at their corresponding high frequency proportion. Overall, this study is consistent with the conceptual network model and suggests frequency as a possible explanation for the preceding third position peak.

Understanding how we recognize letters and build words is central to human language. As soon as a word is recognized, a collection of letters with no individual meaning suddenly becomes something new, meaning none of the discrete letters has. When reading a word, both the identity of a letter and its position within the word is important for word recognition. Suppose the correct positions of the letters within a word are missing. In that case, the collection of letters becomes random, with different meanings or no meaning. Letter and word recognition have continued to be a focus of cognitive psychology papers. Several different models have been introduced to explain different phenomena, such as the Interactive activation model (IAM) (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) that gave insight to the so-called *word superiority effect* that describes the dominance of words when comparing the ability to recognize words versus non-words or even single letters (Reicher, 1969; Wheeler 1970). The basic experiment included a brief presentation of a word or non-word string, followed by a mask. After, participants had to choose between two letters if they were present in the string. For words, letter choices were designed so that both possible letter answers could form a word (e.g., CARD, choices T or D). This ensured that participants recognized the asked letter and did not base their answers on surrounding letters. However, the IAM had a problem regarding the specific position encoding for words: a distinct letter-position entity for every possible combination. First, this fails to explain how one can recall a particular letter's position within a word, since they would be combined into one unity. Second, the model fails when letters within a word are transposed (e.g., computer to comptuer): it is still possible to read and recognize the word. Third, distinct letter-position encodings would lead to a high number of representations, making the realization of one individual representation unlikely due to neurological interference – this is described as the *superposition catastrophe* (von der Malsburg, 1999).

This paper aims to account for some unexpected results found in previous studies regarding how letters in specific positions in words and non-words are remembered and recalled. Studies that have earlier dealt with that topic (Bhouri, 2018; Buijsman, 2019; Donelan, 2018; Freericks, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019; Whittaker, 2019) used the conceptual network by de Vries (2016, 2020), since it can explain position-specific recalls of letters while relinquishing permanent, position-specific encoding. This paper will expand on their findings and look for possible explanations. The conceptual network by de Vries (2005) is based on strengthened connectivity between neurons due to Hebb's rule (1949): cells that fire together (with cell A firing just before cell B) increase their connectivity over time. Clusters of neurons identified based on their reciprocal synaptic strength are called *cell assemblies*. Hebb's rule also implies that these cell assemblies must have a *critical threshold*, a level of activation where the maximum excitation is a necessary consequence, due to self-reinforcing excitation patterns. At the structural level, cell assembly activation below the threshold corresponds to a priming state, while activation above the critical threshold corresponds to the appearance of a representation in working memory. At the functional level, cell assemblies are presenting concepts (e.g., a word or letter) that become vivid in memory (*memory traces*), as soon as the level of activation reach critical threshold within the cell assembly (de Vries, 2020). All nodes in the conceptual network model represent memory traces and can be seen as cell-assemblies at the structural level. The nodes representing letter identities are able to form various connections (Figure 1). Letter nodes can both temporarily bind to locations in the spatial map (SM) as well as to sequence nodes (first position, second position, etc.) in the global sequence network (GSN). The SM is responsible for representing the spatial properties of the external input; the excitation pattern follows the same form as the letter causing its activation. The task network (TN) provides information about the task at hand (de Vries, 2005, de Vries, 2016). Temporary connections are formed when two cell-assemblies from a shared context are activated simultaneously. Notably, the activation level of the letter notes is both *bottom-up* (activation from sensory input) and *top-down* (activation from the word level). Letters that make a word, will receive more activation in the local sequence networks than those who do not; this is especially true when the word note reaches its critical threshold – this explains the aforementioned word superiority effect. The local sequence networks obtain activation both from the GSN (node S1 in the BAT example in Figure 1) and the letter node (B in Figure 1). Next, two requirements must be fulfilled for the local sequence network to become active above the critical threshold. First, it has to hold a representation of the letter B. Second, the letter B must be in the first position. When the binding conditions are fulfilled, two cell-assemblies enter the spike resonance state, where spike patterns within the cell-assemblies are in phase with each other. At a functional level, all words beginning with letter B are primed. However, binding processes cannot occur simultaneously, as spike resonances would suffer from neural interferences. Therefore, the conceptual network includes a scanning mechanism that ensures *binding occurs serially*. This is made by selecting exciting pairs of two cell-assemblies, representing letter identify and letter position.

Figure 1.

The Conceptual Network Model



Note: The conceptual network, as seen in De Vries (2016), including receptors, the scanning mechanism, the task network (TN), the spatial map (SM), word and position nodes (e.g., P1), the global sequence network (GSN), and the local sequence networks represented by position nodes S1, S2, and S3. Dotted Lines represent temporary connections (binding), and solid lines show the activation between the modules. Image retrieved from de Vries (2016).

The conceptual network is able to avoid the superposition effect due to the temporary nature of the node bindings. The strength of the temporary connection between cell assemblies at the binding moment corresponds with the ability to name the *n*-th letter of a word. Consequently, from the serial release of excitation by the scanning mechanism, the activation level of letter nodes drops with every following letter – the *decay effect* (de Vries, 2016). The only exception to this is the last letter. As the last letter has no letter to transfer its activity to, the excitation starts reverberating between the node of the last letter and the node of the previous position. This is called the *reverberation effect* and leads to higher activation of the last letter than previous ones (de Vries, 2016). It is important to note that those two effects only happen to non-words or words that have failed to be recognized. The top-down activation leads to all letter nodes being activated equally as soon as the word is realized.

Using the conceptual network model as the start point of their hypotheses, the previous studies (Whittaker, 2019: Mudogo, 2019; Pink, 2019; Buijsman, 2019; Schwartzkopf, 2019) investigated the ability to recall position-specific letters for 5-letter words and non-words. For non-words, they expected a decline in recall ability from position 1 to 4, with a slight increase in position 5, due to neural decay. This would result in a hook-shaped distribution. Words were expected to show no significant recall accuracy differences between positions. While results confirmed most of this prediction, there was an unexpected peak at the third position for Dutch non-words that could not be explained (Buijsman, 2019; Whittaker, 2019). Other tested languages like German or English did not show this peak. One possible explanation for this unusual peak could be the participants' focus. If the focus was mainly on the middle of the word, the increased ability to recall that letter could be explained. Following those findings, studies by Bhouri, Donelan, Freericks, and Seibel in 2018 tried to use signals at different letters of the word to balance the attention equally across all positions. However, the expected results of a centered warning signal predicting a performance peak for the third position was not found. Results matched the hypothesis of the initial studies with a "hook shape".

This study aims to add a new control variable as possible explanation for the peak at the third letter position. Another possible explanation for the peak could be an unintentionally frequent start frequency of the Dutch non-words. Indeed, since the 3rd letter had to stay on position and was often a vowel, chances are that the first three letters, after rearranging, may have formed a high-frequency head. Therefore, a higher frequency for the first or last three letters could make it easier for participants to recall the third letter position, since the beginning would match the actual word. As explained by the conceptual network model, this would mean significantly higher performance for positions one to three (P1 to P3) compared to the low frequency non-words, since for the first 3 letters, the top-down activation would match with the word, increasing the activation level. This could also explain why this phenomenon was only found in the Dutch trials, should it be due to random letter combinations. To test this, words and non-words with different frequencies for the first and last 3 letters are compared for German, English, and Dutch to test letter frequency as a control variable.

This paper focuses on the impact of the last 3 letter (tail) frequency for German words and non-words. In line with the conceptual network model, tail frequency changes should have little impact to the letter recall ability. More precisely, the letter nodes would fail to excite a corresponding word for the first 3 letters, decreasing top-down activation and hence the recall ability. Since activation level is transferred between letter nodes and P2 and P3 would show little activation, P4 is also expected to show little activation since no excitement could be transferred (decay effect). For P5 the usual performance rise due to the reverberation effect is expected. Overall, this would result in a hook shape distribution for non-words, with no difference between the high and low tail frequency conditions. For words, we expect to replicate previous findings of non-significant differences between letter positions on account of the top-down activation. Tail frequency should also not be relevant for words since the brain is already primed for these letter combinations. The research questions correspond to the following hypotheses: For positions of the high-frequency part of words and non-words, a similar ability to recall letters than for the low-frequency portion of words and non-words. The results should match the previously mentioned hook pattern, as in the first studies in the non-Dutch trials. In addition, higher rates of remembering letters that were part of words than those part of non-words are expected, with no significant drop in accuracy for words across positions.

Method

Participants

The sample was gathered in two ways: Prolific, a platform for paid participants (Prolific, 2022), and a group of first-year Bsc. Psychology students at the University of Groningen. The first group consisted of 43 participants (M_{age} = 25, SD_{age} = 3.29) and received £2 for their participation. The second group consisted of 4 1st-year Psychology Bachelor students at the University of Groningen (M_{age} = 20, SD_{age} = 1.82) rewarded with study points for their successful participation. Participation in the experiment was voluntary, and all participants signed informed consent before it. The total sample size used, comprised 47 individuals (58% female, 100% native speakers, M_{age} = 24, SD_{age} = 3.44, age range 18-30). 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, low tail, and low head, high tail), 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 accuracy of letter recollection. This is given by the accuracy of correctly recalled letters in the performance trials.

Stimuli

The study used paired words retrieved from the CELEX Centre for Lexical Information (2001) database. Each word pair differed in one letter in one position, e.g., BEACH, TEACH. The position where the letter in a pair varies was also the target position the participant had to remember. This accounted for the *word substitution effect* (Reicher, 1969). Surrounding letters of a word can facilitate inferences of the target letter; thus, the word pairs create an ambiguity by decreasing the chance of top-down processes.

For constructing the non-words, we used the same letters as in words since we wanted to preserve similar physical properties and visual appearance for the non-words. This way, when we observe changes in letter accuracy, we can attribute these changes to a letter position and not to the physical properties or the frequency of a letter. The target letters had no obligation to stay at the same position in the non-word of the word.

The non-words in this study were constructed by rearranging the letters of the corresponding word in a manner to have a low head frequency and a high tail frequency. Low head frequency refers to the first three letters that do not form the beginning of relatively common words. Whereas low tail frequency refers to the last three letters that form the ending of fairly common words. Common words in this context have a word frequency of >7 per million words.

The main difference between this experiment and the previous studies is the target letter because the target letter in the earlier studies was at the same position in the word and non-word. In this study, we constructed non-words with a particular frequency. To make this happen, we could not hold the target letter in the same position; otherwise, it would be impossible to construct the desired words. Due to the uncontrollable environment of online experiments, the experiment was designed to be finished in 20 minutes. To achieve this, non-words and words were split up into comparable lists, with each participant only participating in the letter strings of one list. The first, second, and third quartile frequency was used to ensure similarity to make the lists equal.

Procedure

Before the experiment started, the participants gave their informed consent after receiving information about their rights and the nature of the research. 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. For this study, the corresponding participants received instructions about the task they would perform after they signed the consent form. All documents were provided in the German language. The experiment itself was completed online, in an environment of the participants' choosing. Participants were instructed to go to a quiet surroundings with no distractions and complete the experiment on a laptop or PC. Participants had two blocks with ten practice words each, where they could familiarize themselves with the task. To maximize the learning effect, feedback was given after each word.

The stimuli were presented with two hashtags surrounding them, one before the first and one after the last letter. This was done as our visual processing is susceptible to contrasts. That is, the first and last letter's salience (in BEACH, B and H) would be too prominent and have an unfair advantage in contrast to the middle letter positions resulting in a higher recall accuracy for positions 1 and 5. Yet, 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 conceptual network.

The stimuli in the practice and performance trials were presented centrally on the computer screen, in the font size of 24p. This shows an increase in stimuli size by 6p from previous studies, referred to earlier, as previous studies were carried out on bigger screens in a laboratory with 1920x1080 pixels resolution.

The target letter is the letter that the participant should report. For example, if the second letter was asked to be reported, then this letter was the target letter in the corresponding word or non-word. The participants knew which letter was the target letter because below the mask (#@@@@@#), a number was shown, 1 till 5, which corresponds to the letter in the word (as shown in Figure 2).

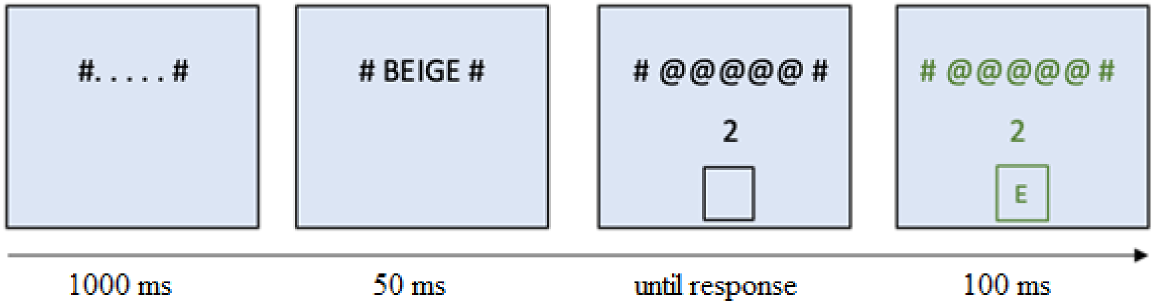
In each trial, four stages followed each other (see Figure 2). The first screen the participants saw was blank. After 1000ms, a preparation signal ("#.....#") appeared on the screen, which lasted for 500ms. The preparation signal indicated where the letters of the word would appear. After the preparation signal, the real target appeared for 50ms ("#WATCH#"). Finally, a mask replaced the target. Below the mask, a number would show up, and the corresponding letter of the (non)-word should be filled in by the participant. This screen was there until the participant filled in a letter and pressed enter. In all situations, the dots, the letters, and the '@'s were surrounded by '#'. This assured consistency on every screen so that the displayed area of the screen stays roughly the same.

The instrument employed to conduct the online study was OSWeb version 1.4.4 and OpenSesame version 3.1 (Mathôt,Schreij & Theeuwes, 2012) The whole experiment included two training blocks and three experimental blocks. Each training block consisted of ten trials; after each word, the participant got feedback about the letter they filled in. If it was the correct letter, the word turned green; if it was the wrong letter, the word turned red. In this way, participants could get familiarized with the task and get the highest score possible in the experimental block without being confused over the task itself. After each training block, the participant received general feedback in percentages, which reflected the accuracy of the recollection of the letters. In the experimental blocks, there was only general feedback at the end of a block to avoid distractions. Each experimental block consisted of 30 trials. In total, each participant was presented with 120 words.

In the end, the participant got three graphs. However, since the experiment was presented online, its duration had to be limited.

Figure 2.

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



Results

The experiment used a within-subjects design, as every participant was tested for all experimental conditions. Consequently, the data were analyzed by using a Repeated measures (RM-) ANOVA. In detail, the three independent variables (word type, letter position, and head/tail frequency) were examined for both main- and interaction effects. The hypotheses for this study expected no three-way interaction between word type, frequency, and letter position. For words, no significant difference in the ability to recall consecutive positions was expected. Non-words, according to the hypothesis, were predicted to have a prominent hook-shape, a significant decrease for the letter positions two, three, and four followed by an increase in position 5, resulting in a hook-shape distribution. Regarding the frequency, we expected no significant difference between low and high tail non-words. Mauchly's test of sphericity assured that the assumption of sphericity was not violated.

The three-way ANOVA produced a significant three-way interaction ($F(4, 184) = 9.781$, $p < .001$). To further investigate those results, four one-way ANOVAs were done, comparing letter positions with frequencies and word type. All four one-way ANOVAs were significant as well. Taken together with the graphs in Figure 3, this means that there is indeed an interaction effect between word type, tail frequency, and position since the distributions are not similar. Tail frequency is an important factor in recognizing and recalling letter positions, especially for non-words (Figure 3), where the differences between high and low tail frequencies are significant for every letter position but the first.

Table 1

Results of the Three-Factor RM ANOVA

Cases	df	F	p	η^2
Word Type	1; 46	326.781897	< .001	0.386063
Frequency	1; 46	35.347237	< .001	0.011972
Position	4; 184	67.486283	< .001	0.134066
Word Type x Frequency	1; 46	28.536123	< .001	0.010060
Word Type x Position	4; 184	20.434807	< .001	0.037776
Frequency x Position	4; 184	11.224285	< .001	0.016690
Word Type x Frequency x Position	4; 184	9.781658	< .001	0.012698

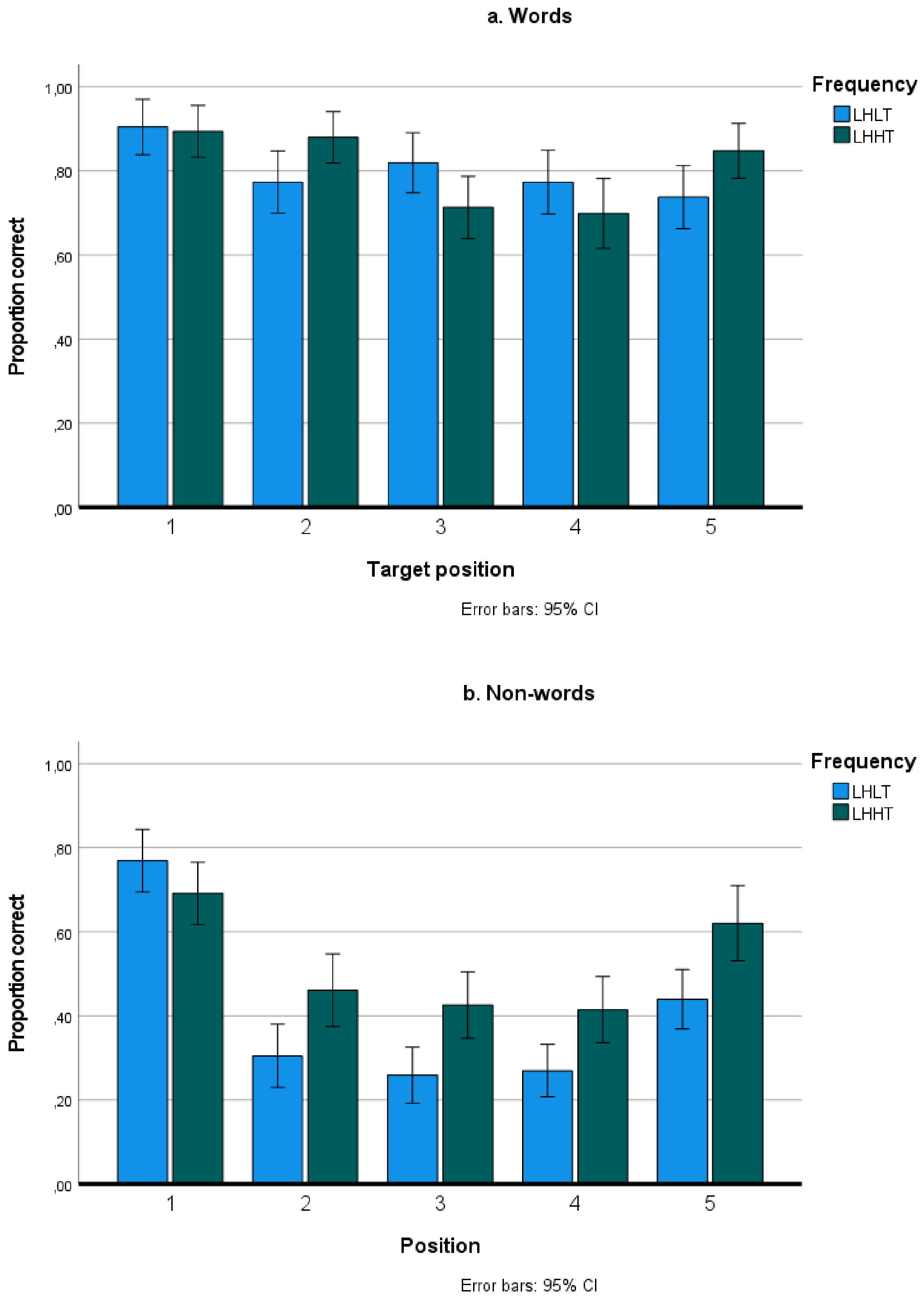
For non-words, the expected hook shape was not fully confirmed. Results in high frequency non-words showed a significant decrease from P1 (M = .691, 95% CI [0.579, 0.804]) to P2 (M = .461, 95% CI [0.349, 0.573]). No difference to P3 (M = .423, 95% CI [0.313, 0.538]) or P4 (M = .415, 95% CI [0.302, 0.527]) and a significant increase to P5 (M = .461, 95% CI [0.349, 0.573])., completing its U-shaped pattern. In the low frequency condition, a significant decrease from P1 (M = .770, 95% CI

[0.657, 0.882]) to P2 (M = .305, 95% CI [0.192, 0.417]) was found, but no further decrease to P3 (M = .259, 95% CI [0.146, 0.371]) or to P4 (M = .270, 95% CI [0.157, 0.382]). There was a significant increase to P5 (M = .440, 95% CI [0.327, 0.552]). Just as the high tail frequency non-words, low frequency non-words also formed a U-shaped pattern. The difference between the high and low tail frequencies are unexpected: with the position 1 being the exception (no significant difference), every other position had the high frequency tails non-words with a significantly better performance than their low frequency tails counterparts. However, it is important to note that the higher frequency indeed resulted in a higher performance in P3.

For words, the results are as expected, there is not much difference between the positions. In the high tail frequency condition (P1 (M = .894, 95% CI [0.7817, 1.006]) had no significant difference to P2 (M = .773, 95% CI [0.661, 0.889]), however there were significant differences between P2 (M = .879, 95% CI [0.767, 0.991]) and P3 (M = .713, 95% CI [0.600, 0.825]), and between P4 (M = .699, 95% CI [0.586, 0.811]) and P5 (M = .846, 95% CI [0.735, 0.960]). In the low frequency results there was only a significant difference between P1 (M = .904, 95% CI [0.792, 1.017]) and P2 (M = .773, 95% CI [0.661, 0.886]), but none in P3 (M = .819, 95% CI [0.707, 0.932]), P4 (M = .773, 95% CI [0.661, 0.886]), or P5 (M = .738, 95% CI [0.625, 0.850]). Generally, significant results were not expected in the word positions.

Figure 3

Mean Responses Across All Conditions



Note. Graph a represents results for words and graph b represents results for non-words. The target position is represented along the X-axis, while the Y-axis represents the proportion of correct responses averaged across participants. Blue bars represent the low head low tail frequency condition; green bars represent the low head high tail frequency condition.

Discussion

The primary purpose of this paper is to check for possible explanations for results found in previous studies (cite studies). Concretely, our experiments added the head and tail frequency of non-words as a control variable as a possible explanation for the peak at the third letter position found previously. This paper focuses on the specific impact on tail frequencies in words and non-words. Multiple hypotheses were made regarding the effects of word-type, frequency, and letter position when checking the ability to recall a specific letter position. In line with the conceptual network model, letter recall accuracy for non-words over letter positions was predicted to resemble a hook shape, with no significant differences between the tail frequencies, due to neural decay and reverberation effects. Further, words were predicted to have a higher recall accuracy than non-words. However, this hypothesis was not confirmed by the results. The graph for both frequency conditions of non-words did not resemble the predicted hook shape but in a U-shaped graph, with no significant differences between positions P2-P4, but all significantly lower than P1 and P5. This contradicts previous findings regarding letter recall performance of non-words that found a hook-shaped pattern (Donelan, 2018; Mudogo, 2019; Pink, 2019; Seibel, 2019; Schwartzkopf, 2019). Nevertheless, similarly to those studies, the prominent performance peak in the third position formerly found by Buijsman (2019) and Whittaker (2019) was absent. This could be attributed to the additional control variable frequency, which was not checked previously. Indeed, a high frequency in P3, when compared to low frequency, led to significantly higher performance and could explain previously found peaks. In addition, we found a significantly higher performance in the high tail frequency non-word condition compared to low tail frequency non-words for P2 to P5. According to the conceptual network model, higher tail frequencies were not supposed to increase letter recall performance. The left-to-right top-down scanning mechanism, with the priming of expected logical successor letters, was thought to have already failed during the previous three letter positions. One possible explanation could lay in the way the non-words were constructed: to keep the visual characteristics of the non-word comparable to the corresponding word, the letters were kept the same, and only the position within the (non-)word changed (e.g., PFAND became FPAND in the high tail frequency). Due to the limited options to create a non-word ending with high frequency, the first two letters were often swapped, while the rest of the word was kept similar. This could mean that non-words with high frequency were too simple, meaning that the Task Network in the conceptual network model could have accounted for the swap of two letters, potentially leading to an identification of the actual word. This could also explain the higher performance in P2 for high frequency tail letters; the higher tail frequency starting at P3 should not have played a role for P2. Indeed, this is somewhat similar to how the Dutch non-words were constructed in the first set of studies: since the 3rd letter had to stay in position and was often a vowel, chances were that the first three letters, after rearranging, may have formed a high-frequency head.

Another possible reason for the higher performance of the high frequency tails could be that during the presentation of non-words, some word nodes may get primed (without reaching critical threshold). This priming may cause better performance on the last two positions since top-down excitation is position-specific.

Words were predicted to elicit no significant differences between consecutive positions for both frequency conditions. According to the conceptual network, recognized words give rise to a strong top-down excitation of their inherent letters, resulting in high recall performance at each position. Nevertheless, the analysis showed a significant decrease from P2 to P3 and a significant increase from P4 to P5 in the high tail frequency condition. For the low tail frequency words, only a significant decrease from P1 to P2 was present.

As previously mentioned, this study was part of a more extensive set of experiments focused on the impact of head and tail frequencies on the ability to recall position-specific letters (Kabil, 2022; Malea, 2022; van der Wal, 2022; Yu, 2022). The main goal was to further explore the previous findings by Buijsman (2019) and Whittaker (2019), namely the performance peak at the third position for non-words. All of the studies on the group found a significantly higher recall performance in the third position compared to low-frequency positions. In addition, every study was able to find significant interaction effects between frequency, word-type and letter position on letter recall ability. The high head frequency studies showed a significant difference between the first three positions compared to the following positions four and five.

Summarizing, frequency could have influenced the performance peak, however, it is unclear how exactly it led to a spike in only one position.

This study had some limitations that are important to mention when rating its explanatory power. First, the experiment was conducted online, which could have impacted the results in multiple ways. Due to the limited time considered realistic to maintain concentration in an uncontrolled, potentially distracting environment, not every participant was tested for every (non)word. Second, word lists were tried to be comparable regarding frequencies; however, this could have increased the overall noise of the results. This could partially explain the differences between positions when recalling letters from words, since some words might not be as well-known as others, leading to an unrecognized word in the short time frame.

Recognizing words is essential in our everyday life. Studies like this broaden our insights into how letter and word perception are connected. A potential application for this could lay in creating words and texts with increased readability or emphasizing specific parts of words to improve the reading flow.

As a consequence of being a follow up study, the conditions were kept as close to the original studies as possible. Accordingly, the word length was held at 5 letters. This severely limited the amount possible of non-word manipulations while keeping the tail frequency high. For future studies, changing the word length to create a more significant difference between non-words and words could generate more profound insights into the influence of tail frequency. This study supports the serial letter binding of identity and position brought up by the conceptual network. The increased ability to recall letters in the first and the last positions for non-words found in this study aligns with previous findings supporting the model. Building on that, frequency was found to be a significant predictor of recall performance amongst word-type and letter position.

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