The Effect of Tail Frequencies on Binding of Specific Position in (Non)Word and Letter Recognition

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Abstract

Previous research found that letter recall accuracy for five-letter English-like words (English, Dutch, German) showed a U-shape pattern, except for five-letter Dutch words outside the third letter position, which appeared to be an unexpected peak. Therefore, other studies have explored this with a focus on warning signals but did not find a significant difference. Based on previous research, this thesis conducted follow-up research, used the Conceptual Networks as an essential theoretical basis, and used masked priming for position-specific letter-recall tasks. This experiment tested the effect of different tail frequencies on position-specific recall accuracy of letters in (non)words. 62 participants (12.9% native English speakers) conducted an online the n-th letter task at home. The variables on top of this were the different positions of the letters tested and the different tail frequencies in different word types. The experimental results showed that English five-letter words did not peak in the third position, but this study supported a U-shaped distribution in the non-words under both the tail frequency condition. Future studies should expand the number of participants and, as far as possible, align the participants' native language with the language of the words tested.

Keywords: letter recognition, position-specific, word frequency, Conceptual Network

The Effect of Tail Frequencies on Binding of Specific Position in (Non)Word and Letter Recognition

Language is a uniquely human higher function, and the mechanisms of language comprehension have been studied in various research areas. Among these is the increasingly sophisticated study of the representational processing of language in cognitive neuropsychology (e.g., Cattell, 1886; Reicher, 1969; Wheeler, 1970; Rumelhart & McClelland, 1982; O'Reilly & Munakata, 2000; Dehaene, 2002; Kemmerer, 2014; de Vries, 1998, 2004, 2016, 2020). In an early study, James Cattell (1886) demonstrated that most people can still understand the meaning of the misspelled English-like words in a passage of text. Specifically, Grainger and Whitney (2004) called the phenomenon the jumbled word effect and conducted a further study. Recent research addressed that people recognize words correctly more often than the same letter, called the word-superiority effect (Reicher, 1969; Wheeler,1970; Baron & Thurston, 1973; Mason, 1982; Grainger & Jacobs, 1994; Grainger & Whitney, 2004). The current study followed the earlier studies (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019), which used the n-th letter task and conceptual network (Dalenoort & de Vries, 2004; de Vries, 2016) on position-specific recall. The present thesis addressed the effect of specific letter position on accuracy based on the word-superiority effect to understand the factors that affect reading and help people read more efficiently.

The word-superiority effect means that the context facilitates the recognition of letter stimuli in a word. In early study, Reicher (1969) experimented with stimulus materials and was presented with a tachistoscope (An apparatus for presenting visual stimuli in short bursts): single letters, words made up of four letters, and strings of meaningless letters made up of four letters. The different materials consisted of words and non-words, and the subjects were asked to select the letter in the specified position in the stimulus just presented.

Reicher's experiment showed that recognition of letters in words was better than recognition of letters in single letters or non-words. He believed that this effect occurred because people collect visual information and then process it through our knowledge through the top-down conceptual information. However, Reicher (1969) did not explain the phenomenon of discrepancies that arise when letters provide similar information. For instance, the differences between “WORD” and “WORK” cannot be shown in the experiment.

Furthermore, Grainger and Whitney (2004) improved Reicher’s (1969) experiment and proposed that a relationship between letter recognition and letter position could explain the word-superiority effect. They used the masked-priming technique to evaluate the mechanisms in letter-position coding. Mask-priming techniques allow for automated machining processes. *Automatic processing* is the process by which the brain processes information unconsciously, without participants needing attention or behavioral control over the responses formed. Grainger and Whitney 's (2004) experiment has shown that the effect of target-word recognition was related to word length, and to explain this phenomenon, they proposed *position-specific slot encoding*. Several previous studies (Rumelhart & McClelland, 1982; Peressotti & Grainger, 1999; de Vries, 2004, 2016; Schoonbaert & Grainger, 2004) have examined the effect of position-specific slot encoding; the visual perception of the words is based on a location gradient, i.e., a left-to-right viewing order, which explains the primary effect. The leftmost letter is often seen as the initial letter and is recognized more quickly and accurately (Lefton et al., 1978; Rumellhart, 1981; de Vries, 2016). This suggests that one slot for each possible letter position, for instance, the word “DAD” could be coded by D_1, A_2, and D_3, while A_1, D_2, and D_3 coded the word “ADD”. Position-specific slot encoding was developed by McClelland and Rumelhart (1981), who demonstrated the interactive activation model (IAM).

The IAM is primarily used to process word recognition in context. The model assumes that perceptual processing occurs at different levels, with different levels processing different inputs of information, such as the visual level, the letter level, and the word level. The IAM demonstrates a top-down information process at the knowledge-to-word level. IAM has the assumption that vision is processed in parallel so that the brain can simultaneously process information at a spatial scale, for example, words with four or more letters. The model assumes that perception is processed top-down and bottom-up simultaneously. The interaction of different pieces of information consists of some processing units, each with an entity called a node linked to a large number of other nodes in a way that generates arousal (one node supports the presence of another) or inhibition (nodes contradict each other). Each node has an activation value at a given time influenced by direct input and interactions between nodes, producing a neuron-like process of excitation and activation (McClelland & Rumelhart, 1981).

However, a limitation of the IAM is that it does not explain how people can still understand these jumbled words because the combination of letter position and identity is homogenized. When letter nodes are activated, the particular letter of the word that appears in the corresponding position is also activated. As a result, letters in the activated word receive more arousal than other letters, while other non-target letters are inhibited. This could explain the word-superiority effect. However, because letter positions are combined with letter identities and fixed, it is challenging to present target words that have slightly different target words, for instance, two words that are composed of the same letters but have different letter orders ("dad" vs. "add"), IAM could not explain the difference. In addition, there is the computational complexity of word recognition alone, which requires a large amount of space to store the fixed positions of the different letter identities. In addition to IAM, we can also learn about the well-known sequential encoding regulated by oscillating inputs within alphabetic units (SERIOL, Peresotti & Grainger, 1999; Whitney, 2001; de Vries, 2016). Due to the limitations of the IAM, previous studies (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019) did not use IAM as their theoretical explanation.

However, previous studies (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019) did not choose SERIOL (Whitney, 2001) as well. SERIOL consists of five processing layers that demonstrates the impact of attention on the relationship between letter position binding and letter identity during word recognition. The part on word recognition is interpreted at the functional level (as opposed to the structural level, which focuses on the biological level, the functional level focuses on information processing). It is proposed that the position in terms of letters is not fixed but, when activated, is context specific; however, SERIOL cannot explain the phenomenon of recognition when position-specific letter units are missing, leading to a failure in explaining the n-th letter task. Meanwhile, it does not explain the relationship between word and letter recognition at the structural level.

The above model does not elucidate how the brain archives position-specific recall; for instance, the problem of recognition from word to letter level from specific letter locations is not explained. However, de Vries (2016) proposed a model to address the problem of the conceptual network. Location is essential in perceiving words and recognizing letters in the conceptual network. Moreover, the concept of cell assembly (CA) is proposed through the principle of neural connectivity. CA refers to a cluster of neurons having more and stronger connections to other clusters of neurons. It is also the core of the theory on which this paper is based. Through extensive descriptions, we know that the representation of identity and position must be separate. Otherwise, we would need large memory stores or be unable to process combinations of letters at all, for example, not being able to distinguish between “as” and “sa” (The problem of different interpretations of SERIOL). At the structural level, the conceptual network proposes that the connections between the neurons that make up the network form cellular assemblies.

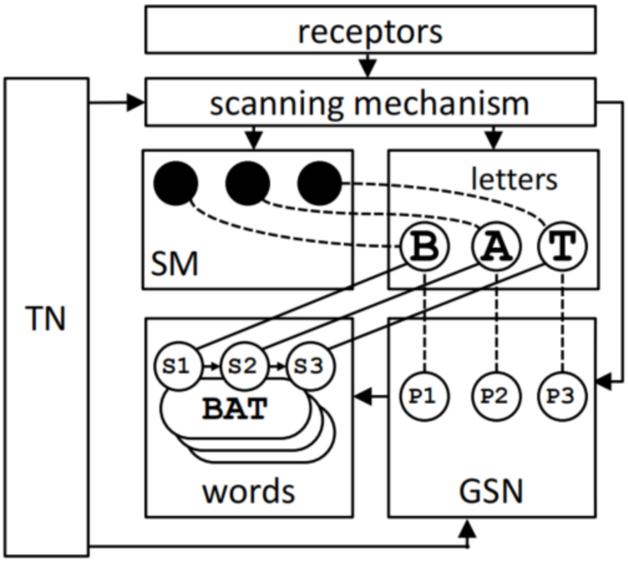
In contrast, the Tanzi-Hebb rule leads to the simultaneous triggering of activation of recurrent neurons, which leads to an increase in connectivity between neurons that necessarily have a critical threshold (CT; Hebb, 1949; Tanzi, 1983; Hecker and Passmore, 2013). In other words, it necessarily rises to its maximum activation excitation level; without this activation, the strength of the connection gradually decreases (de Vries, 2020). At the functional level, CA would correspond to a memory trace or concept, for which the hypothesis has also been put forward that CA-forming neurons contain memory traces that need to be widely distributed to ensure mental stability.

Letter nodes can be temporarily bound to locations in the Spatial Map (SM) and nodes representing sequences in the Global Sequence Network (GSN). The SM ensures the binding between letters identification and position through excitation patterns within the map. Binding will manifest in two directions, one is propagation, and the other is reverse inhibition (Figure 1). Moreover, binding and activation overlap, which would explain that we form new memories or activate memory traces. Moreover, the difference between some memories being inhibited and some being abnormally excited when expressing memories can be explained. However, the temporary connections in the network are critical if a neural binding exists. Because all the memory traces involved can directly activate the relevant CA, permanent connections would drive all memory traces, which is unrealistic. Therefore, in a conceptual network, we assume that two cell assemblies or more cell assemblies will form temporary resonances through which they achieve activation of each other. The condition for being able to achieve simultaneous activation, then, is to reach CT and form tip resonances (de Vries, 2016).

This temporary connection also requires several conditions. The first is the simultaneous activation of several cell assemblies, and the second is the sub-network of the starting CA. The constraints are in place so that there is no confusion. The conceptual network assumes the existence of a scanning mechanism that allows letters to enter the network one after the other, allowing positions and identities to be paired, which would prevent inference of activation. An SP represents the position. The process of serial binding can be tested by a letter recall task, which means that participants are presented with a series of words and provided with a number for each word indicating a particular position of a letter in the word, and then asked to answer the correct letter. Assuming that the binding process would be disturbed, the strength of the connections between the SP and the memory trajectory used for the letter representation and the strength of the temporary connections between the location nodes in the GSN would also decay. Moreover, the last position would be anomalous because the excitation does not go to the next node anymore but instead echoes back between the last position and the last letter node, enhancing the last letter connection, also called the reverberation effect (de Vries, 2016).

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 (i.e., binding). Image adapted 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.

In conclusion, at the functional level, the activation of word nodes up to CT or higher, and thus the activation of more CAs, explains the superiority effect on words by understanding them. While excitation and inhibition must be in play, this requires CA activation to be temporarily connected. At the structural level, the rapid, partially serial process is the neural substrate of experience. Thus in the letter recognition task of the previous studies (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019), there is a hook-shaped pattern for the letter recognition from non-words. In other words, the hook-shaped pattern shows that the accuracy of the letter recall starts from the first letter of the five-letter word and decreases to the fourth position, with a significant increase in accuracy for the last external position (Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019). In addition, due to top-down activation in words, we expected participants to have higher recall accuracy for words compared to non-words, explaining the study by Bhouri (2018), Donelan (2018), and Freeicks (2018). In addition to top-down activation, the process of bottom-up self-organization and local element activation is also essential in word recognition.

Except for English, previous studies also had experimented with Dutch (non) words, and in a slight departure from the hook-shaped pattern just mentioned, Buijsman (2019) and Whittaker (2019) found that Dutch (non) words had significantly higher accuracy for recall in the third position in the letter recognition task, forming a W-shaped pattern. Thus, to explain this unexpected finding, the previous study (Donelan, 2018; Freericks, 2018; Seibel, 2018; Whittaaker, 2018) suggested that it might be a warning signal as the critical factor that influenced the experiment. Nevertheless, they did not find significant differences in the attention or no attention condition. However, all the above studies predict no significant differences in words with both warning signals at each position.

Building on these findings, the present work was designed to test whether it could be the tail frequencies could explain the peak in the third position of Dutch nonwords with mean recall accuracy. The words mentioned in the experiments were all composed of five letters; the same word lengths were used as in the previous experiments to ensure differences in accuracy due to different word lengths (Grainger & Whitney, 2004). The tail frequencies describe the frequencies of the last three letters in the (non)word. We selected words with low head (last three letters) high tail frequencies and low head high tail frequencies for the experiment. Thus, the accuracy of letter recalls, and the relationship between high and low tail frequencies was verified. This study hypothesizes that for non-words, we expect that a hook-shaped pattern will form in low-head and low-tail frequencies and then increase slightly in the 4th and last letter position (Hypothesis 1a). For low-head and high-tail frequencies, a relatively similar pattern because of the bottom-up serial binding, but the position of the figure at the 4th and last letter position is slightly higher than the letter recall shown for low-head and low-tail accuracy (Hypothesis 1b). Whereas for word conditions, it was hypothesized that there were no differences in letter accuracy across word position; in addition, the mean recall accuracy will be higher for words than non-words with each condition (Hypothesis 2).

Method

Participants

The sample used was gathered by means of 1st-year Sona Practicum Pool (A system for psychology freshmen to participate in psychological experiments set up by the Psychology Department of the University of Groningen). Participation in the experiment was voluntary, and all participants signed informed consent (see Appendix A) prior to it. The total sample size 62 (45 participants did not give age and gender data, for other 17 participants who gave data: 11 females, 6 males, 2 other, M_{age} = 27.03, SD_{age} = 15.24, age range 18-30) we used. Only 8 participants (12.9%) were English native speakers, 11 (17.7%) were not English native speakers, and 45 participants (69.4%) were unknown. Participants completed the experiment for receiving SONA credits for fulfillment of PSBE1-28 course requirements. 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: fix the first three letters as low head frequency, change the frequency of the last three letters, high tail vs low tail frequency), 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 means 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 only differed in one letter in one position (e.g., BEACH vs TEACH). The position where the letter in a pair varies was also the target position the participant had to remember. This was done to account for the *word superiority effect* (Reicher, 1969). Reicher believed that when words were missing a letter and the reason for participants could fill in the correct letter of the word was that the key letter correctly recalled is unique, and the accuracy would relate to the word frequency. For instance, for a five-letter word, the frequency of the first three letters is what we call head frequency, and the frequency of the last three letters is what we call tail frequency. High frequency indicated a word frequency of seven or more times per million words. Thus, participants might be able to guess the target letter by just its surroundings; the word pair creates ambiguity where the exact letter must be correctly remembered. It is to better explore the effects of word frequency, position and the presence or absence of words with real meaning on reading recognition and memory.

As we known, our visual processing is very sensitive to contrasts. We tested one letter in the five-letter word to looking forward to the relationship of serial binding, then, we add symbols around the first and letter positions, to accurately test their recall according to the conceptual network. The target letter is the letter that the participant should report. The target letter can be any letter in the word (e.g., word: BTACH, 5 positions from left to right can be marked as “1”, “2”, “3”, “4”, “5”, and the number would be shown under the target letter while the target letter was masked). Participants are asked to recall the exact letter of the position that has been masked. If the second letter was asked to be reported, then this letter (for the example “BTACH”, then “B” should be reported) was the target letter in the corresponding word or non-word. For the participants, they know which letter was the target letter because below the mask (#@@@@@#), a number was shown, 1 till 5, which indicated the position from 1 to 5 (as shown in Figure 2).

For constructing the non-words, we used the same letters as in words since we wanted to preserve similar physical properties for the non-words. This way, when we observe changes in letter accuracy, we can attribute these changes to a letter position and not only the physical properties or the frequency of a letter.

The non-words in this study were constructed by rearranging the letters of the corresponding word in a manner to have a low head low tail frequency and a low head high tail frequency. Head frequency refers to the first three letters that form the beginning of relatively common words. In the meanwhile, tail frequency refers to the last three letters that form the ending of relatively common words. Low head low tail frequency word means having a word frequency less than 7 per million words. Whereas low head high tail frequency word means having a word frequency of >7 per million words.

The main difference between the stimuli setting in the previous studies ((Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019) is the target letter because the target letter in the previous studies was at the same position in the word and non-word. But in this study, we constructed non-words with a certain frequency. To make this happen, we could not hold the target letter in the same position, otherwise, it would be difficult to construct words with certain frequencies.

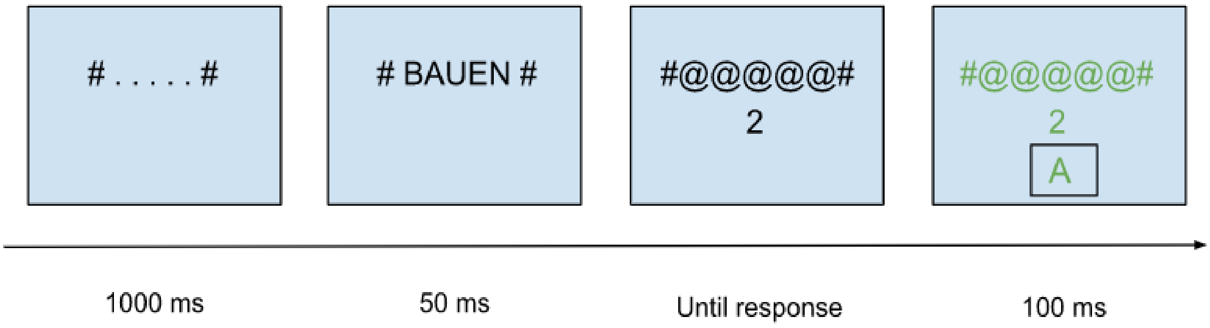
Procedure

Before the experiment started, the participants gave their informed consent (see Appendix A) after receiving information about their rights and the nature of the research though SONA system. They were informed that their age, gender (data were collected from Qualtrics), and performance would be collected and that they could contact the principal investigator via mail, should there be any questions. For English experiment, the corresponding participants received instructions about the task they would perform after they signed the consent form. The experiment itself was completed online, in an environment of the participants’ choosing. Participants were instructed to go to a quiet surrounding 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 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 (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019) were carried out on bigger screens in a laboratory with lower resolution (1920 x 1080 pixels).In each trial, four stages followed each other (see Figure X). 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 ‘@’ were surrounded by ‘#’. This assured consistency on every screen, without a screen which otherwise would be bigger than the other screens. The software employed to conduct the online study was OSWeb version 1.4.4 and OpenSesame version 3.1 (Mathôt et. al., 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 right 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 were only the general feedbacks at the end of a block, each experimental block consisted of 30 trials. In total, each participant was presented with 120 words. In the end, the participant got three graphs. 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.



Once the experiment was complete, the participant could decide when to do the next test. The detail could be found in Appendix D.

Analysis

The experiment used a within-subjects design, as every participant was tested for all experimental conditions. Consequently, the data were analyzed using repeated measures (RM-) ANOVA. In detail, the three independent variables (word type, letter position, and tail frequency) were examined for both primary- and interaction effects. We use four one-way analyses of covariance because our data are not independent, and variables can interact with each other. In the study, the dependent variable was the mean of the accuracy of the recall letters, and the independent variables were frequency, word type, and letter position. To understand the three-way ANOVA, we need the four one-way ANOVA to determine the significance of the differences between these position means in each of the four cases.

Results

Raw data about the mean RTs of correct responses were aggregated and restructured on SPSS. The mean accuracy data were analyzed in a 2x2x5 repeated measures analysis of variance (RM-ANOVA). The hypothesis included the effect of frequency for positions in non-words and words, while the high-tail frequency words would have better mean recall accuracy than the low-tail frequency words. The assumptions also included that those words would have equal performance over positions, while the averaged accuracy response would have a hook shape for non-words. The different position patterns mean accuracy for these four cases and do not imply a three-way interaction. SPSS test all assumption by running Mauchly's test of sphericity. The Greenhouse-Geiser (GG) correction and pairwise comparisons with Bonferroni corrections were analyzed for non-word conditions. To assume the assumption, the frequency differences would only be found in non-words rather than words. From Figure 3, there was a hook shape for non-words and a different hook shape for low-tail frequency than for high-tail frequency. However, the differences in mean accuracy also occurred in words. We also expect an interaction effect between word type and position. For example, in the three-way RM ANOVA (Table. 1), significant differences for frequency tail, letter position, and word type ($F(4,196) = 22.980$, $p = 0$, $\eta 2=.910$) interaction effect, which indicates that the mean accuracy was distinct for each factor. As hypothesized, tail frequency and letter position should have a significant interaction effect; the mean accuracy of the high tail frequency nonword was expected to be significantly higher than the mean accuracy of the low tail frequency nonword, then the four one-way ANOVA analyses need to be considered.

Low-tail frequency, non-words

It was assumed that the non-words with low-tail frequency would show a hook-shaped distribution. Therefore, the data should have a high mean of Position 1 and then decrease till Position 3, then have a slight increase from Position 4 to Position 5. The mean in Position 5 should be much lower than the mean of Position 1. The significant main-effect of five positions with low-tail frequency for non-words were found (F (4,196) = 79.990, *p* = .000, η^2=.13.167). A post hoc pairwise comparison using the Bonferroni correction showed different significant results between different positions. The analysis indicated a hook shape distribution (see graph a in Figure 3), while Position 1 (M = .817, 95% CI [.757, .877]) to Position 2 (M = .360, 95% CI [.281, .439]) had a significant decrease, p < .05. Position 2 (M = .360, 95% CI [.281, .439]) to Position 3 (M = .197, 95% CI [.136, .257]) had a significant decrease, p < .05. While Position 3 (M = .197, 95% CI [.136, .257]) and Position 4 (M = .200, 95% CI [.145, .255]) had no significant difference, p > .05. Furthermore, the analysis indicated a most significant increase from Position 4 (M = .200, 95% CI [.145, .255]) to Position 5 (M = .487, 95% CI [.405, .568]), p < .05, meanwhile, it was showed a significant decrease from Position 1 (M = .817, 95% CI [.757, .877]) to Position 5(M = .487, 95% CI [.405, .568]), p < .05. This result supported the expected deep hook pattern and the hypothesis mentioned before.

High-tail frequency, non-words

The significant main-effect of five positions with high-tail frequency for non-words were found (F (4,196) = 28.536, *p* = .000, η^2=4.690). A post hoc pairwise comparison using the Bonferroni correction showed different significant results between different positions. The analysis indicated a hook shape distribution (see graph a in Figure 3), while Position 1 (M = .640, 95% CI [.578, .702]) and Position 5 (M = .650, 95% CI [.558, .742]) had no significant difference, p > .05. Therefore, to compare graph a and b in Figure3, we found a different hook shape. Furthermore, the analysis indicated a most significant decrease between

Position 1(M = .640, 95% CI [.578, .702]) to Position 2(M = .350, 95% CI [.273, .427]), p < .05, while the analysis showed a significant decrease from Position 1 (M = .640, 95% CI [.578, .702]) to Position 3 (M = .330, 95% CI [.262, .398]). Position 2(M = .350, 95% CI [.273, .427]), and Position 3 (M = .330, 95% CI [.262, .398]) had no significant difference, p > .05. Position 3(M = .330, 95% CI [.262, .398]) and Position 4 (M = .467, 95% CI [.392, .541]) had a significant increase, p < .05, which shown from Position 3 the mean started increasing. Furthermore, the analysis indicated a significant increase from Position 4 (M = .467, 95% CI [.392, .541]) to Position 5 (M = .650, 95% CI [.558, .742]), p < .05. It would be predictable that the analysis supported a significant increase from Position 3 (M = .330, 95% CI [.262, .398]) to Position 5 (M = .650, 95% CI [.558, .742]). In contrast, there are no peak on position 3 found in this experiment.

Low-tail-frequency, words

The significant main-effect of five positions with low-tail frequency for words were found (F (4,196) = 8.771, *p* = .000, η^2=.702). A post hoc pairwise comparison using the Bonferroni correction showed different significant results between different positions. In the hypothesis, the result should show no significant differences between each position. However, the analysis indicated a line shape distribution (see graph b in Figure 3), while Position 1(M = .877, 95% CI [.828, .925]) and Position 2 (M = .837, 95% CI [.756, .917]) had no significant difference, *p* > .05, Position 2 (M = .837, 95% CI [.756, .917]) and Position 3 (M = .760, 95% CI [.692, .828]) had a significant decrease, p <.05. Meanwhile, Position 3 and Position 4 (M = .737, 95% CI [.648, .825]), Position 4 and Position 5 (M = .763, 95% CI [.680, .846]) , both had no significant difference, p >.05. This result support the hypothesis 2. In graph b (Figure 3), the result was close to the shape of a straight line, but with a small increase in variation at Position 2 and Position 3.

High-tail frequency, words

The significant main-effect of five positions with high-tail frequency for words were found (F (4,196) = 13.271, p = .000, η^2=1.108). A post hoc pairwise comparison using the Bonferroni correction showed different significant results between different positions. However, the analysis indicated a line shape distribution (see graph b in Figure 3), while Position 1 (M = .907, 95% CI [.856, .957]) and Position 2 (M = .817, 95% CI [.732, .901]) had a significant decrease, p <.05, while Position 2 and Position 3(M = .723, 95% CI [.641, .806]) had a significant decrease as well, p <.05. There was a significant increase between Position 4(M = .740, 95% CI [.658, .822]) and Position 5 (M = .833, 95% CI [.753, .914]), p <.05. Meanwhile, Position 3(M = .723, 95% CI [.641, .806]) and Position 4 had no significant difference, p > .05. This result does not support the hypothesis 2. In graph b (Figure 3), it also shows a flat U shape.

Table 1.

Three-way RM-ANOVA Analysis

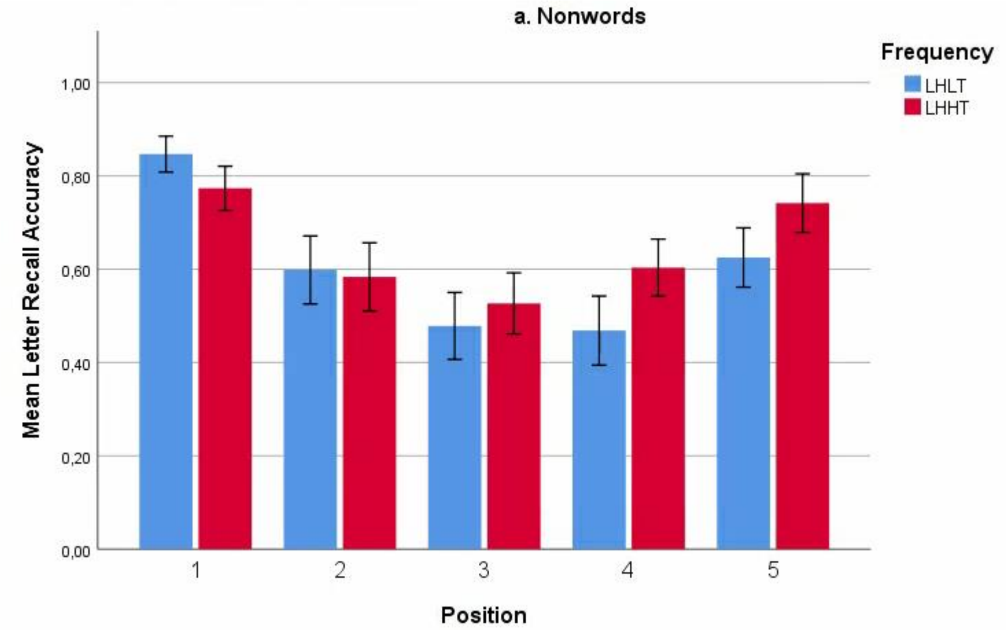
	η^2	*df*	*F*	*Sig.*
Frq	,448	1;49	17,994	,000
Pos	1,901	4;196	62,175	,000
TarType	30,567	1;49	327,482	,000
Frq * Pos	1,405	4;196	21,445	,000
Frq * TarType	,272	1;49	11,156	,002

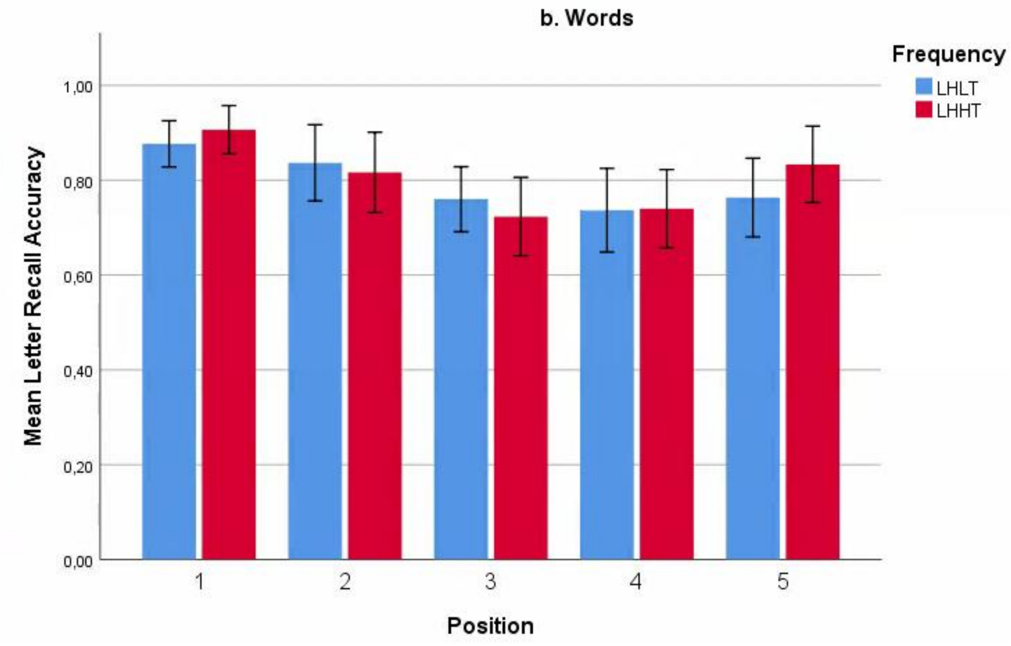
Pos * TarType	,022	4;196	27,409	,000
Frq * Pos * TarType	,910	4;196	22,980	,000

Note. a Computed using alpha = ,05

Figure 3

Mean Responses Across Experimental Conditions





Note. The error bars are 95% CI for Graph a and b. Graph a represents results for non-words and graph b represents results for words. The X-axis represents the target position, while the Y-axis represents the proportion of correct responses across participants. Blue bars represent low frequency words or non-words, while red bars represent high frequency words or non-words condition.

Discussion

This study hypothesizes the effect of word frequency (low head, low tail-frequencies vs. low-head high tail-frequencies) and word type (word vs. nonword) on letter recognition accuracy in specific positions. The main concentration was nonword, with low tail-frequencies, which has found a peak at the third position on the letter recognition task on Dutch nonword (Buijsman, 2019; Whittaker, 2019). In line with earlier studies ((Bhouri, 2018; Donelan, 2018; Freericks, 2018), a hook-shaped pattern will be formed in both conditions for nonwords. However, the result did not support Buijsman’s (2019) and Whitaker’s (2019) study because there was no position 3 underlying position-specific recall peak, indicating that the tail frequency does not cause the hypothesized effect. Top-down activation in serial binding occurred because the nonwords are arbitrary letters. Given the first to last position binding and corresponding activation of word nodes, we do not expect an effect for a high tail, given that a low head precedes it. Position 3 is extraordinary in the five-letter word. It was not only in tail-frequencies that no peaks were found in position 3, but also in the head-frequencies of the English nonword of Malea (in preparation), in other German (Kabil, in preparation; Schoell, in preparation) and Dutch (der Wal, in preparation) of head-frequencies and tail-frequencies as independent variables, no peaks were found in position 3. Some possible explanations, firstly, there were only 62 subjects in our experiment, and the sample data was insufficient. Second, the material for Buijsman's (2019) and Whittaker's (2019) experiments was Dutch, and perhaps the frequencies of non-words in Dutch do not differ significantly from the frequencies of words, making it difficult to distinguish the effect of word frequency in this experiment. Third, the frequencies of words and non-words in our design differed significantly, subject to the language itself, and we did not ensure that the words used in the experiment had similar high or low frequencies; we tried to ensure that the frequencies were as reliable as possible but were limited by the frequencies of the words themselves. Also, the peak in position 3 found by Buijsman (2019) and Whittaker (2019) is not a particularly significant difference and may be subject to error. We hope that future experiments will take these factors into account.

The current findings support the idea that in letter recall accuracy, the performance on words is much better than nonwords in both conditions, which shows the word-superiority effect (Bhouri, 2018; Donelan, 2018; Freericks, 2018; Bujisman, 2019; Mudogo, 2018; Pink, 2019; Seibel, 2019; Schwarzkopf, 2019; Whittaker, 2019). In addition, the study hypothesis was met that different tail-frequencies on nonwords in specific positions will have a hook-shaped pattern. It has been mentioned that a hook-shaped pattern expects the letter recall accuracy to decrease from position 1 to position 3, then increase until the last letter position. On the other hand, a less steep hook shape is expected for the mean recall accuracy on low tail frequencies compared to high tail frequencies (Hypothesis 1a & 1b). There should be no significant differences for words in all conditions with each position (Hypothesis 2), but this hypothesis has not been supported.

The conceptual network model supports us in deriving a series of predictions and provides an excellent theoretical basis for our findings. The dominance effect of all the experimentally discovered words is then explained by binding the identity and position of letters, which can form permanent connections capable of being activated. The first letter performs best because of the primacy effect, with a gradual decrease in accuracy starting with the second letter, while the position, 5, will have an improved accuracy compared to position

4 because of the reservation effect since after the last letter no CA needs to be activated anymore. This means less interference with the activation of the following letter position. According to the conceptual network model, there should be no significant difference in letter accuracy between position 2, position 3, and position 4, as all three positions suffer from attenuation of activity during binding, weakening the strength of the temporary connection. However, our experiments do not support this hypothesis (hypothesis 2).

Furthermore, for word accuracy recall, it appears that accuracy should be unaffected by the word's frequency and the letter's position. However, our experiments found a different result, i.e., a slight decrease from position 1 to position 3. This suggests that words are affected by CT between words, i.e., when the word is stimulated in a way that does not reach CT, the word is not recognized; when it is stimulated in a way that reaches CT, it is recognized as a word. Therefore, CT has a vital role in the recognition of letters.

Limitations and Future Directions

There are still many limitations to this experiment. Firstly, the experiment was done entirely by the participants at home. Therefore, there is no guarantee that the participants will all be in the same environment (noise, availability of time, size of computer screen, etc.). In addition, it was not possible to determine whether the participants had fully understood the steps correctly or whether they were used to the study through practice, as the fact that the experiment was conducted at home prevented them from communicating with the researcher in a timely manner and answering their questions. Whether participants had problems during the experiment, we cannot know, and it can be assumed that the presence of these problems would affect the accuracy of the data. Therefore, to ensure the reliability of the results, we should do more experiments of this type in the future, in the laboratory, in the same environment as much as possible.

Secondly, we required that participants' first language be English, but only 12.9% (8 participants) of the participants we collected were clearly native English speakers. This may have been a factor that influenced the results of the experiment, reducing the distinction between words and non-words and affecting the variability of words in different positions. It is possible that their native language (non-English) may have contributed to their incorrect processing of English words when testing some words. This includes the fact that both British English and American English have spelling differences, resulting in high frequency words that are shown in the database, but are low frequency words in the participants' personal experience. Or perhaps some words were non-words in the participant's personal experience. These relate to our previous discussion of the importance of CT, which is difficult to achieve when participants are not sufficiently familiar with the words, resulting in words being identified as non-words and causing inconsistency with the hypotheses.

Finally, Phonology may also be a factor, and future research could explore the relationship between letter recall and word pronunciation. For example, there would be a question of whether phonology is activated automatically through visual processing at a similar level. Moreover, there is no cue that phonological intervention could affect our ability to recognize the meaning of words or even correctly recall the letters in a particular position in a word.

Theoretical and Practical Implications

In our experiments with letter positions and word frequencies as well as word types, we focused on tail frequencies. We found that tail frequency had a significant impact on the accuracy in recalled letters. In our experiments, we used five-letter words, and future experiments could be designed with length as a variable. This study of ours, in part, validates the conceptual network theory. More importantly, it will be useful for people studying fast reading and improving dyslexia in groups such as ADHD. And, the experiments with letter recognition can be applied in real life, for instance, in advertising or Bionic reading.

Conclusions

To summarize, the present experiment supports the view that the frequency of positional binding of letters in a particular position of the recall sequence is instrumental in the accuracy of letter recall. The speed of recall varied between positions of the (non)words. In the specific neural binding hypothesis, this is of great significance for reading speed. That is, word frequency can affect the accuracy of letter recall, and increasing word familiarity can deepen the positional neural binding link and play a role in ignition speed.

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Appendix A: Consent

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INFORMED CONSENT

“WORD READING AND COUNTING”

PSY-2122-S-0254

- I have read the information about the research. I have had enough opportunity to ask questions about it.

- I understand what the research is about, what is being asked of me, which consequences participation can have, how my data will be handled, and what my rights as a participant are.

- I understand that participation in the research is voluntary. I myself choose to participate. I can stop participating at any moment. If I stop, I do not need to explain why. Stopping will have no negative consequences for me.

- Below I indicate what I am consenting to.

Consent to participate in the research:

- Yes, I consent to participate voluntarily in the study described in the study information sheet.
- Yes, I consent voluntarily to that my personal data will be collected for the purposes described in the information sheet of this study, that they will be anonymized accordingly, and that these anonymized data will be used and analyzed as described in this information sheet.
- Yes, I consent that the measures described in the information sheet of this study guarantee my privacy to the maximal degree.
- Yes, I consent voluntarily that after July 6th, 2022, I can no longer withdraw my data from the collection of this study.

[ ] Yes, I consent to participate;
[ ] No, I do not consent to participate.

Consent to processing my personal data:

[ ] Yes, I consent to the processing of my personal data as mentioned in the research information. I know that until 06-07-2022 I can ask to have my data withdrawn and erased. I can also ask for this if I decide to stop participating in the research.
[ ] No, I do not consent to the processing of my personal data.

You have the right to a copy of this consent form. We suggest taking a screenshot via your smartphone, or your computer.

Appendix B: Participant Information Form

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INFORMATION ABOUT THE RESEARCH

VERSION FOR PARTICIPANTS

"WORD-READING AND COUNTING"

PSY-2122-S-0254

Researchers

- *Dr. Pieter de Vries (Department of Experimental Psychology), Charlotte Axmann, Mariam Kabil, Melina Malea, Lukas Schoell, Ruoyu Yu, Ylse van der Wal.*

- **Why do I receive this information?**
  - *You are invited to take part in a research study of Word-reading and counting. We need participants who are fluent English speakers, Dutch speakers, and German speakers.*

- **Do I have to participate in this research?**
  - *Participation in the research is voluntary. However, your consent is needed. Therefore, please read this information carefully. Ask all the questions you might have, for example because you do not understand something. Only afterwards you decide if you want to participate. If you decide not to participate, you do not need to explain why, and there will be no negative consequences for you. You always have this right, including after you have consented to participate in the research.*

- **Why this research?**
  - *We are investigating the relationship of letter position on word-recognition.*

- **What do we ask of you during the research?**
  - *In this research, participants will complete a simple response-task.*
  - *The task is a computer tasks which is online, includes practicel trails and experiment trails.*
  - *If you agree to participate in this study, we will ask you to attend a brief presentation of a letter-string and report a letter presented at a given position.*

- **What are the consequences of participation?**
  - *We do not anticipate any risk to you participating in this study.*
  - *This study will help to better understand the effect of letter position in word recognition. It may facilitate new methods of text presentation or text processing algorithms at later stages.*
  - *You will be awarded SONA-credits or euros for participating in this study. According to the standards of your platform. If you are a volunteer, you will not be rewarded.*

- **How will we treat your data?**
  - *Your only personal data we will use are:*
    - *Your study identifier, i.e., a nine-digit number, you will get at the start of the experiment.*

    - *Your platform-specific identifier, necessary to grant the compensation agreed on the platform (unless you are a volunteer),*
    - *Your age and sex.*
    - *Your performance data, i.e., your responses to each of the trials in the experiment. These will be collected online by means of the computer on which you perform the task and will be analysed according to the methods appropriate for this type of research.*
  - *We will ask your consent to collect the mentioned personal and performance data and to handle and protect them anonymously.*
  - *After your data has been collected, it will be indexed by your study identifier. If you want access to your data, mail p.h.de.vries@rug.nl with reference to this identifier.*
  - *After you have given your consent, you can still choose to withdraw your data from the collection of this study until July 4th 2022 If so, also mail p.h.de.vries@rug.nl with reference to the study identifier. After this date we will remove the all above-mentioned identifiers from the stored data and we can no longer select or remove your individual data.*
  - *When you timely mail us to have your personal data erased, they can be removed instantly.*
  - *Once the identifiers are removed, it is highly unlikely that the data can be traced back to you.*

- **What else do you need to know?**
  - *You may always ask questions about the research: now, during the research, and after the end of the research. You can do so by speaking with one of the researchers present right now or by emailing (p.h.de.vries@rug.nl) one of the researchers involved.*
  - *Do you have questions/concerns about your rights as a research participant or about the conduct of the research? You may also contact the Ethics Committee of the Faculty of Behavioural and Social Sciences of the University of Groningen: ec-bss@rug.nl.*
  - *Do you have questions or concerns regarding the handling of your personal data? You may also contact the University of Groningen Data Protection Officer: privacy@rug.nl.*
  - *As a research participant, you have the right to a copy of this research information.*

Appendix C: Advertisement

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TARGETED ADVERTISEMENT

Did yuo konw taht yuor brian cna raed jumbeld wrods?

Were you able to read this? This happens due to the remarkable ability of our brain to recognize and read jumbled words. The human mind reads words as a whole and not every letter by itself; therefore, we aer albe to eaisly raed tihs setnecne!

Do you want to test your letter recollection of jumbled words? This is a chance to challenge your memory and attentive skills. To participate in this experiment, you will need to use a laptop/computer. Please note that it is *not possible* to use your *cellphone*. During the experiment ensure that you are in a quiet place without distractions to enable your optimal concentration.

Appendix D: Instructions of the Experiment

Instructions for experiment

Please fill in the following questions on your demographics:

- Sona number, nationality, age, sex

Dear participant,
Welcome to the study *Test your letter recollection of Jumbled Words*! You can expect the following experiment to take roughly 15-20 minutes to complete. As this experiment requires a lot of concentration and in order to ensure optimal performance, we kindly ask you to carry out the experiment in a quiet environment.

Procedure of experiment

Training Blocks

The experiment will start with two training blocks which will consist of ten 5-letter sequences each. The training block starts with a blank screen. After that, you will see a preparation sign (# . . . . . #). Next, the 5-letter sequence will appear for 50 ms (1/20 of a second) in capital letters between both "#"- symbols (e.g., # BEIGE #). Finally, a mask will appear on the screen (#@@@@@#) with a number from 1-5 below it, that indicates a letter position. Please fill in the letter corresponding to that position and note that the "#"-symbols are not included in the count. If by mistake, you typed in a wrong letter, there is a possibility to correct this by just typing in the new letter. As soon as you click 'enter', you are taken to the next word. You cannot correct the letter after you click 'enter'.
In this section, you will receive feedback following each answer, indicating whether your response was correct or incorrect. All words and symbols are shown in black. After entering the letter and tapping the 'Enter' keyboard, all symbols on the screen will become red or green, as indicated in *Figure 1* below. The red colour will denote a wrong response, whereas a green colour indicates a correct response.

Figure 1. An example of the sequence of screens in a training block, with a correct answer.

Experiment Blocks

Then, there will be three blocks of the experiment itself. Each block contains 40 words. After each block, feedback on your performance is given, the percentage of correct answers. For clarity, *Figure 2* below indicates what you will see on each of the screens. After a blank screen is shown, you will see a preparation sign (# . . . . . #). Next, the 5-letter sequence will appear for 50 ms (1/20 of a second) in capital letters between both "#"- symbols (e.g., # BEIGE #). Finally, a mask will appear on the screen (#@@@@@) with a number from 1-5 below it, that indicates a letter position. Please fill in the letter corresponding to that position and note that the "#"-symbols are not included in the count. If by mistake, you typed in a wrong letter, there is a possibility to correct this by just typing in the new letter. As soon as you click 'enter', you are taken to the next word. You cannot correct the letter after you click 'enter'. Note that reaction time is irrelevant for the experiment. If the experiment is going too fast for you, you can adjust the speed by waiting before pressing enter. In addition, we recommend taking a break between blocks to ensure optimal performance. You can have a break with unlimited time. At the end of each block, the accuracy of your responses will be shown on the screen in the form of a percentage of the correct answers you gave.

Figure 2. An example of the sequence of screens in the experiment blocks.

Explanations of Graphs at the end:

Design 1: low head, low tail, low head, high tail

In total, you are going to be presented with three graphs.

Graph 1. Overall Performance of Words vs. Non-words.
The first graph shows the overall performance of word vs. non-words. It indicates your general performance in both words and non-words. On the X-axis, you see the different letter positions of one until five. Per position, you can see 2 bars indicating the percentages for words and non-words, respectively. The dots that you see indicate the percentage of the letters you correctly recalled.

Graph 2. Letter Recall Performance for Non-words.
The second graph portrays the letter recall performance for non-words. The bars show the expected results from our hypothesis. There are 2 bar colours: red for high frequency on the last 3 letters and black for low frequency on the first 3 letters. High frequency stands for common letter combinations for the last 3 letters; likewise, low frequency stands for uncommon letter combinations for the first 3 letters. The dots that you see indicate the percentage of the letters correctly recalled; this way you can compare your performance to the expected results. The numbers on the x-axis indicate the specific letter position.
This graph shows your performance specifically for non-words.

Graph 3. Letter Recall Performance for Words.
The 3rd graph you get to see portrays your letter recall performance for words. The number below the bars indicates your performance for that specific letter position. If you look at the bars in the graph, they correspond to the expected results of the experiment. There are 2 bar colours: red for high frequency on the last 3 letters and black for low frequency on the first 3 letters. High frequency stands for common letter combinations for the last 3 letters; likewise, low frequency stands for uncommon letter combinations for the first 3 letters. If you look at the dots, they correspond to the achieved score, this is your performance on the experiment. In this way, you can see how you scored for the letter recall performance for words, compared to the expected results.

Design 2: low head, low tail, high head, low tail

In total, you are going to be presented with three graphs.

Graph 1. Overall Performance of Words vs. Non-words.
The first graph shows the overall performance of word vs. non-words. It indicates your general performance in both words and non-words. On the X-axis, you see the different letter positions of one until five. Per position, you can see 2 bars indicating the percentage for words and non-words, respectively. The dots that you see indicate the percentage of the letters you correctly recalled.

Graph 2. Letter Recall Performance for Non-words.
The second graph portrays the letter recall performance for non-words. The bars show the expected results from our hypothesis. There are 2 bar colours: red for high frequency on the first 3 letters and black for low frequency on the last 3 letters. High frequency stands for common letter combinations for the first 3 letters; likewise, low frequency stands for

uncommon letter combinations for the last 3 letters. The dots that you see indicate the percentage of the letters correctly recalled; this way you can compare your performance to the expected results. The numbers on the x-axis indicate the specific letter position.
This graph shows your performance specifically for non-words.

Graph 3. Letter Recall Performance for Words.
The 3rd graph you get to see portrays your letter recall performance for words. The number below the bars indicates your performance for that specific letter position. If you look at the bars in the graph, they correspond to the expected results of the experiment. There are 2 bar colours: red for high frequency on the first 3 letters and black for low frequency on the last 3 letters. High frequency stands for common letter combinations for the first 3 letters; likewise, low frequency stands for uncommon letter combinations for the last 3 letters. If you look at the dots, they correspond to the achieved score, this is your performance on the experiment. In this way, you can see how you scored for the letter recall performance for words, compared to the expected results.