Left-to-Right Serial Binding In A Masked Priming Task: An ERP Study

Robin van Grieken

S3280896

July 2019

Master thesis Msc Cognitive Psychology and Psychophysiology

Faculty of Behavioural and Social Sciences

University of Groningen

Supervisors: dr. P. H. de Vries & dr. A.A. Wijers

Abstract

The effects of three different prime types on ERP data, and reaction time and accuracy were analyzed for a lexical decision task containing 8-letter and 9-letter (non-)words. Begin primes consisted of the first four (in the 8-letter condition) or five (in the 9-letter condition) letters of the target (non-)word followed by distractor letters (1234(5)dddd). End primes consisted of the last four or five letters of the target (non-)word preceded by distractor letters (dddd5678(9)). Unrelated primes consisting of only distractor letters (dddddddd(d)) were added as controls. In word trials: begin prime trials led to lower reaction times than both the other prime types, and end primes led to lower reaction times than unrelated primes. A significant interaction effect between word type and prime was also found on reaction time. No effect was found on accuracy, nor was there any priming effect in the non-word trials. ERP results showed an earlier, more positive component in begin prime trials. Higher positivity was recorded from around 200 ms to around 400 ms post stimulus onset. Results support the left-to-right serial binding hypothesis of the conceptual network (de Vries, 2016): a general model applied to written word recognition stating that, one after the other, neural representations of letter identities and -positions become temporarily bound by means of existing temporary neural pathways.

Keywords: conceptual network, left-to-right serial binding, visual word recognition, orthographic processing, lexical decision

Introduction

Written language is something we deal with every day. From reading novels or a master's thesis we, seemingly effortlessly, process printed script. This process starts with *orthographic processing*, the recognition of single written words, as words are the orthographic objects in our language (Grainger, 2008). The underlying dynamics of written word recognition are very interesting and widely researched. This study aims to be a link in the greater network of studies trying to find answers for the many questions we are still left with.

Goal of this study

Many models of written word processing are based on the principles of the Interactive Activation model (McClelland & Rumelhart, 1981). This model assumes, among other things, that processing of every letter in a word happens in parallel. This study, like two previous studies using similar paradigms (Looden, 2016; Zhou, 2018), aimed to find evidence for a left-to-right serial process of word recognition. In the study by Looden (2016): a priming task was used containing three different prime types: begin primes, end primes, and unrelated primes. Begin primes consisted of the first four or five letters of the target word, which depended on whether the target word consisted of eight or nine letters. 8-letter words were primed by four letters and 9-letter words were primed by five letters. Begin primes (e.g. 'poli' for 'politiek') were denoted as 1234(5); end primes (e.g. 'tiek' for 'politiek') consisted of the last four or five letters, again depending on the length of the target word, and were denoted as 5678(9); and unrelated primes consisted of four or five distractor letters, denoted as dddd(d) (e.g. 'skip' for 'politiek'). In the study by Zhou (2018): distracter letters were added to the primes (1234(5)dddd; dddd5678(9); dddddddd(d)). The length of the primes and the number of relevant letters again depended on the length of the target word. This study used the same priming paradigm as the study by Zhou (2018). An overview of previous studies involving priming is given first, after which the theory of this study is discussed.

Priming literature review

As briefly mentioned: one of the earliest and most influential models of orthographic processing is the Interactive Activation (IA) model (McClelland & Rumelhart, 1981). This model is fairly straightforward in its description of the word recognition process: feature detectors exist for the underlying features of each letter. These feature detectors send activation to letter detectors, which send activation forward to word detectors. This principle is known as *slot-coding* because each letter is connected to a particular position, or slot, independent of a specific word. A schematic display of the model is shown in Figure 1. Feature detectors activate letter detectors that correspond with a certain position. Word detectors that contain those letters at the corresponding position then receive activation. When the correct word detector is activated above a critical threshold, as in this case the word ‘work’ would be, it will inhibit the activation of neighboring words, in this case ‘fork’ and ‘word’. According to this model: the processing of all letters within a word happens in parallel, meaning all letters are processed at the same time (McClelland & Rumelhart, 1981).

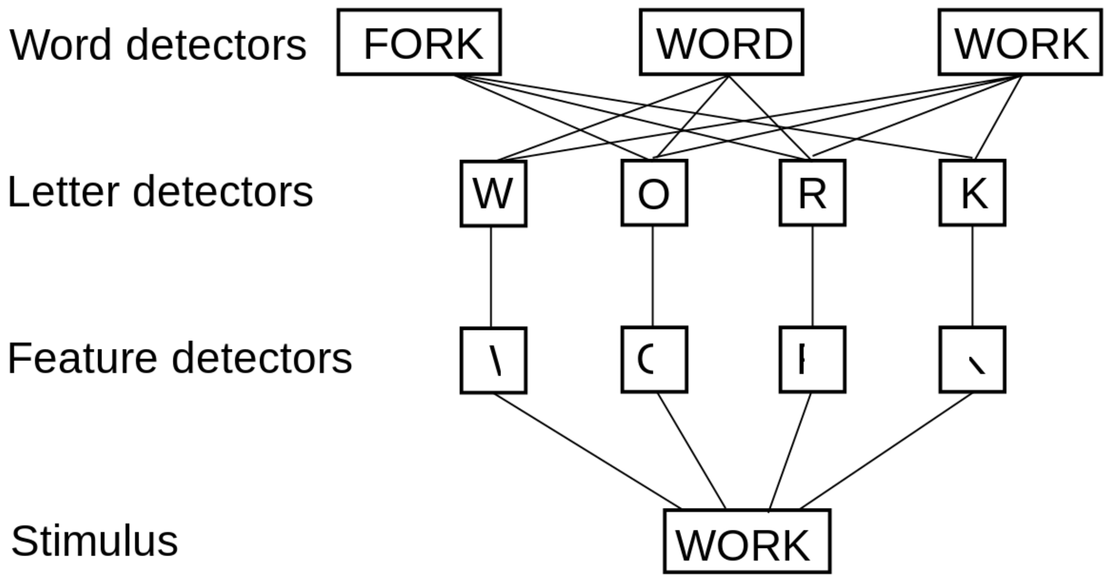

Figure 1: schematic representation of the Interactive Activation (IA) model as proposed by McClelland and Rumelhart (1981), showing a stimulus in the form of the word ‘work’, feature detectors that are activated by specific features, letter detectors that receive activation from these feature detectors, and word detectors that are activated by the letter detectors (Retrieved from: https://en.wikipedia.org/wiki/Word_superiority_effect#/media/File: Word_superiority_effect. svg)

Later studies found results that could not be explained using the IA model. One of which, performed by Humphreys, Evett, and Quinlan (1990), demonstrated that a priming effect can be achieved while using orthographically related non-word primes of a different length than the target word. The target words in this study consisted of five letters and the primes consisted of four (the use of incomplete or concatenated primes is now known as *subset priming).* It was found that primes that shared the first four letters (1234) led to significantly more facilitation than transposed primes (1435) or outer-letter-only primes (1dd5) (Humphreys et al., 1990). This demonstrated the effects of orthographic overlap between stimuli of different length and forced a reconsideration of the way letter-position is encoded during orthographic processing (Grainer, 2018). The IA model could not explain this because it is based on the assumption that letter position and identity is processed simultaneously and the right letter nodes are only activated when the absolute letter position in the word is intact.

In a 2009 study, Grainer and Holcomb conducted further research into the principle of subset priming. They compared ERP results of a masked priming task with two different conditions. In the relative-position condition, primes were concatenated versions of the target word in which only relative letter positions remained intact (cllet for COLLECT). In the absolute-position condition, primes were hyphenated versions of the ones used in the relative-position condition (c-lle-t for COLLECT). They found that differences could be found in the ERP components between the two conditions. Early N250 components were sensitive only to hyphenated primes, with the N250 being smaller in the related prime condition than the unrelated condition. This supported a model by Grainger & Van Heuven (2003) stating that the different ERP components signaled a shift of orthographic information from one level of processing to the next. According to this model, letters within a word are processed in parallel and the early N250 takes place when orthographic information is being sent from location-specific letter detectors to a *"location-invariant, word-centered, prelexical orthographic code (relative position map)"* (Grainger & Holcomb, 2009). From there the orthographic information is sent onto a whole-word orthographic representation, signaled by the late N250 component. When a word is activated, the semantic knowledge associated with this particular word becomes active as well. This is signaled by the early N400 component (Grainger & Holcomb, 2009). The presence of the early N250 component in the hyphenated condition only supports this model and suggests that this component is associated with processing of location-specific letter identity (Grainger & Holcomb, 2009).

In a later study, Ktori, Midgley, Holcomb and Grainger (2014), used superset primes instead of subset primes. So rather than taking relevant information out of the primes by removing letters, irrelevant information was added by supplementing letters. The study contained an unrelated letter condition, where unrelated letters were added to the prime words (maurkdet for MARKET); a hyphenated condition, where hyphens were added to the prime words (ma-rk-et for MARKET); and an identity priming condition where prime and target words were the same (market for MARKET). All three conditions were compared to an unrelated prime condition. It was found that, like subset priming, superset priming could lead to significant facilitation compared to the unrelated primes. However, hyphen-inserted primes caused a much stronger effect than letter-inserted primes. Likely: this has to do with the 'double interference' caused by letter-inserted primes, as letter-inserted primes cause interference in letter position and in letter pair information. Hyphen-inserted primes only cause interference in absolute letter position information (Ktori et al., 2014). With regards to ERP results in this study: effects emerged later for both types of superset primes compared to identity priming. Hyphen-insert priming effects showed up in the N250 time-window, and letter-insert primes even later, namely in the N400 time-window. Possibly, the inhibition of mismatched letter pairs in whole-word activity took longer than the activation caused by matching information (Ktori et al., 2014). In this study, parallel processing rather than left-to-right processing was assumed.

Aforementioned findings proved priming is quite robust against changes in letter position and word length and were difficult to explain using the principles of the IA model. More flexible models were needed to explain the increasing amount of new findings in priming studies. Examples of these models are: the open bigram model (Grainger & van Heuven, 2003), the Sequential Encoding Regulated by Inputs to Oscillations within Letter units (SERIOL) model (Whitney, 2001), and the Overlap model (Gomez, 2008). The open-bigram model is made up of the standard IA model, but with added bigram detectors. This means words were coded using ordered letter pairs (Grainger & van Heuven, 2003). This made the model more flexible by making the assumptions regarding letter position less strict. Even when some letters are transposed, enough bigram detectors could still be activated to significantly prime the target word. The basic principles of slot coding and parallel processing still apply. A schematic representation of the model is shown in Figure 2.

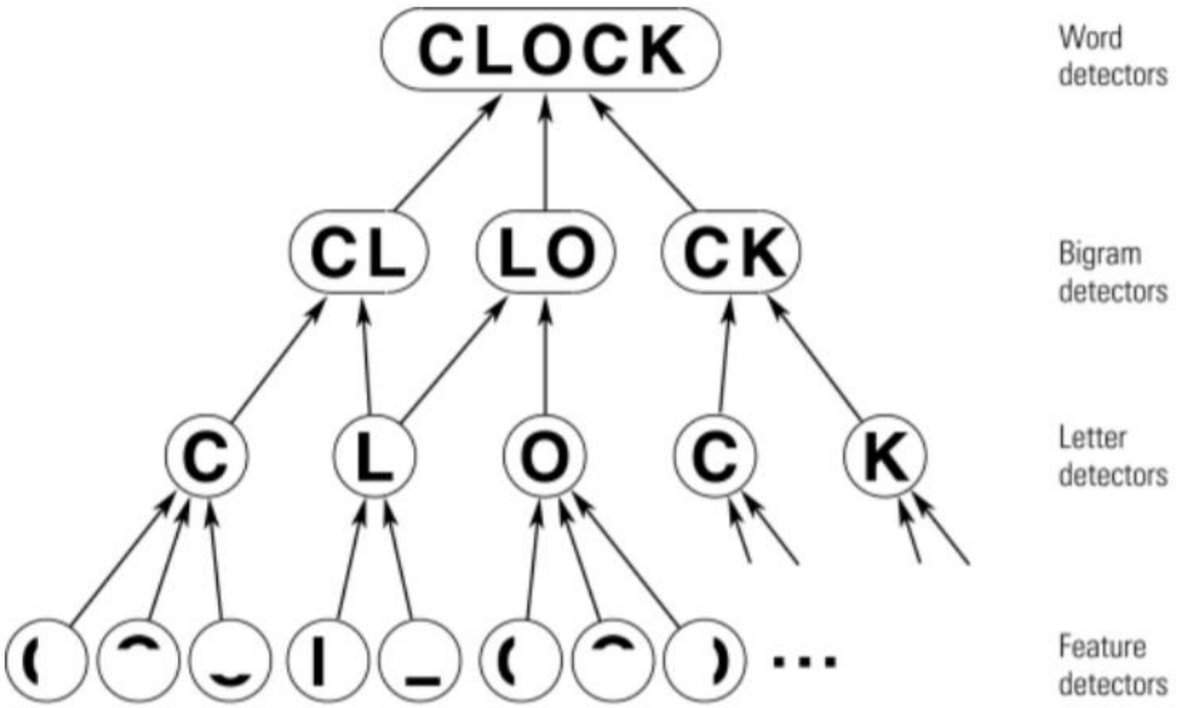

Figure 2: Schematic representation of the IA model with added bigram detectors (Grainger & van Heuven, 2003), showing feature detectors sending activation to letter detectors, which activate bigram detectors and ultimately the word node for ‘clock’ is activated (Retrieved from: https://dogsbody.psych.mun.ca/_notes/3450/Chapter%203.pdf)

The Overlap model (Gomez, Ratcliff & Perea, 2008) is quite similar to the original IA model in that a certain letter is activated at its set location (P). The main difference with the IA model is that this model also assumes activation of that same letter on P-1 and P+1. The SERIOL model (Whitney, 2001) is a little more elaborate and consists of five levels of processing, starting at the pixel level and ending at the word level. Activation decreases from left to right so the first letter is activated first while lateral inhibition makes sure no two letters are activated simultaneously. These models leave more flexibility in the associations between letter identities and their location within a string (Grainger & Holcomb, 2009). Most of the aforementioned models assume a similar parallel processing as proposed by the IA model (McClelland & Rumelhart, 1981), with the exception being the SERIOL model (Whitney, 2001) which does assume left-to-right serial processing. A schematic representation of the SERIOL model is given in Figure 3.

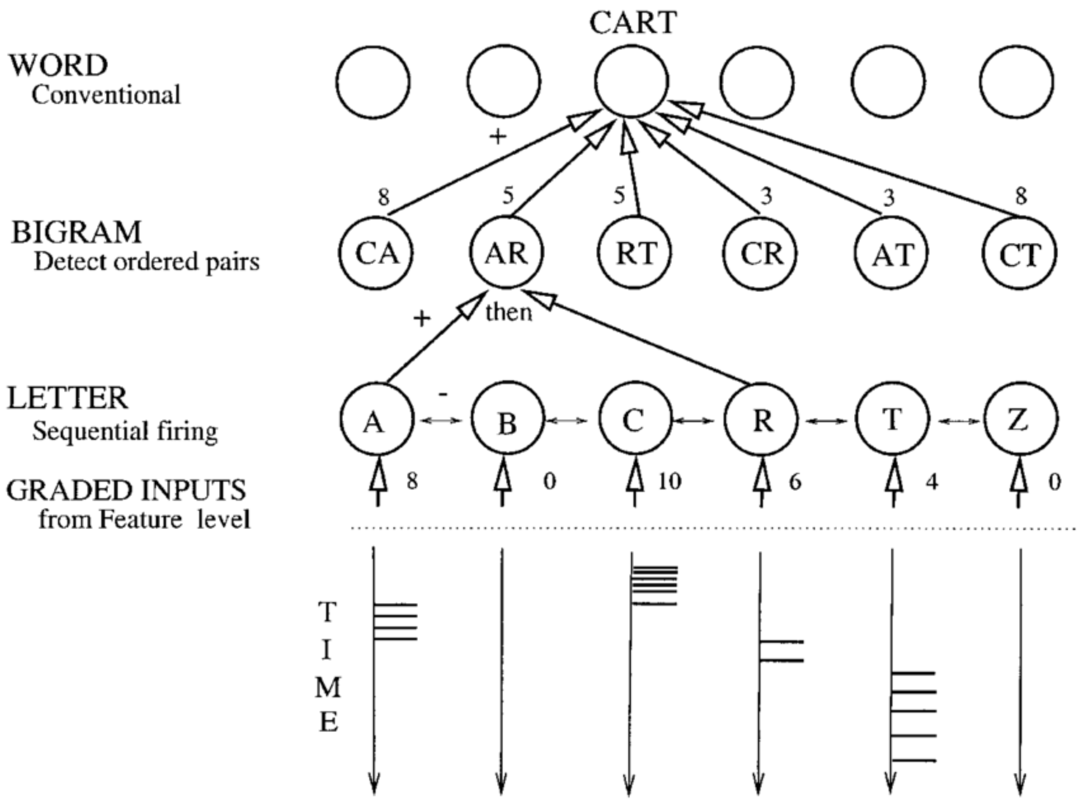

Figure 3: Schematic representation of the SERIOL model showing the timeline, grades in activation, letter and bigram detectors, and finally activation of the word note (Whitney, 2001).

Coming back to the robustness of priming: Marzouki, Meeter & Grainger (2013) demonstrated in a study that a priming effect showed when the location of the target word varied horizontally on the screen compared to the location of the prime word. This means that when letter detectors are pre-activated, these letters are more easily recognized even if they're presented on a different location on the screen. This suggests that a lot of the information carried over from the prime to the target is done by location-invariant orthographic representations, providing evidence for a general mechanism for location-invariant processing of visual objects (Marzouki et al., 2013). Related studies (Dufau, Grainger & Holcomb, 2008; Ktori, Grainger, Dufau & Holcomb, 2012) using a similar experimental paradigm in combination with EEG found location-independent ERP signals around 200 ms post-target onset (Marzouki et al., 2013). This is around the time that activation is thought to be passed on from location-specific letter detectors to location-invariant word-centered sublexical orthographic representations (Grainger & Holcomb, 2009). As the study used only single (pseudo-)letters, no parallel or serial process takes place here.

The strength of priming effects can be influenced by a number of factors, for example: Massol, Grainger, Midgley, and Holcomb (2012) demonstrated that pronounceable non-words are more sensitive to priming effects than non-words made up of a string of consonants. The experiment entailed a post-cued letter identification task using non-words, where participants had to reproduce a certain letter of the presented non-word. Both types of non-words were primed by a string of letters that either shared the first or the last five letters (of the total seven letters) with the target letter string. It was found that pronounceable non-words had a significantly stronger priming effect compared to consonant strings. They proposed that pronounceable non-words were processed further, as they would activate both orthographic and phonologic representations. These representations should be more robust and less sensitive to the effects of masking. ERP results seemed to support this: ERP components for pronounceable non-words and consonant strings were identical in the first phase but started to differ around 200 ms. Suggesting that the first phase of processing, location-invariant single letter processing, is identical for both types of non-words. Differences after 200 ms indicated the higher level processing present for pronounceable non-words but absent for consonant strings (Massol et al., 2012). These findings could possibly be explained by the influence of phonological information on orthographic processing. Another possible explanation is the higher similarity between pronounceable non-words and real words leading to higher activation in word nodes making them more sensitive to priming. Interestingly, the study by Massol et al. (2012) also tested initial vs final overlap primes, comparable with the begin and end prime used in this study. Massol et al. (2009) found larger negative components in initial overlap (comparable to begin prime) trials. The study used a more elaborate version of the IA model which assumes parallel processing.

Meade, Grainger, Midgley, Emmorey & Holcomb (2018) researched a different ERP component and demonstrated an association between lexical processing and the N400 component. The paradigm used consisted of a lexical decision task in which participants were primed with words with either high- or low-density orthographic neighborhood, meaning they either had many or few orthographic neighbor words (Meade et al., 2018). It was found that, for participants who scored high on spelling, words from high-density orthographic neighborhoods that were primed by a close neighbor word led to slower reaction times and a stronger reversed N400 response. This was explained by the inhibitory effect that words have in interactive-activation models (Meade et al., 2018). The activation of a certain word leads to the inhibition of neighboring words to prevent interference. This would mean that, because the initial inhibition of the target word has to be overcome, lexical processing of the target takes longer and costs more cognitive effort. The paradigm used in this study is also based on the IA model and thus assumes parallel processing.

Related to the use of orthographic neighbors as primes is the embedding of the target word in the primes. It has been found that when a target word is primed by a word with the target embedded in it (scandal for scan), this typically leads to inhibition or a null effect. When a target word is primed with a non-word that has the target embedded in it (scanald for scan), facilitatory effects have been found (Grainger & Beyersmann, 2017). For both ‘scanald’ and ‘scandal’ the relative positions of the letters in ‘scan’ are unchanged, but there seems to be an inhibitory effect of ‘scan’ by the above baseline activation of ‘scandal’. This suggests that recognition of a word within another word (scan in scandal) costs more cognitive effort than whole word processing. Comparisons can be made between the paradigm used by Grainger & Beyersmann (2017) and the one used in this study. In both, the prime features (part of) the target word and distractor letters. However, in Grainger & Beyersmann (2017) the prime is an actual word (and a different length than the target), which is more likely to cause interference.

A conceptual network

Although more and more models have been developed to become more robust and accurate, none of the aforementioned models proposes a solution to the *binding problem*. In this study: binding refers to the temporary neural pathways between letter identity, letter position, and letter location within the brain (de Vries, 2016). The binding problem is the lack of a biologically plausible explanation for this process. The absence of this explanation in the previously discussed models is not strange, as those are functional models and their purpose is to explain and predict research findings This can be done without explaining the underlying processes. The problem arises when looking at the structural level, because this calls for an explanation of the mechanisms involved. This is where a conceptual network (de Vries, 2016) comes in to provide a possible solution to the binding problem.

A conceptual network based on the principles of self-organization. This means the functioning of the system is based on the local interactions of the elements within the system. Each node within a conceptual network represents a cell-assembly: a cluster of neurons that are more strongly interconnected than they are connected to neurons in other clusters (de Vries, 2016). Necessarily, each cluster must have a critical threshold: if enough neurons in the cluster are excited from outside, the excitation in the cluster will remain active, even if excitation from the outside stops. At the functional level, a cluster corresponds to a memory trail that is then active in working memory. Alternatively, if clusters of neurons are activated but do not reach the critical threshold, a word will be in a state of priming. A schematic representation of the word recognition process in a conceptual network is shown in Figure 4.

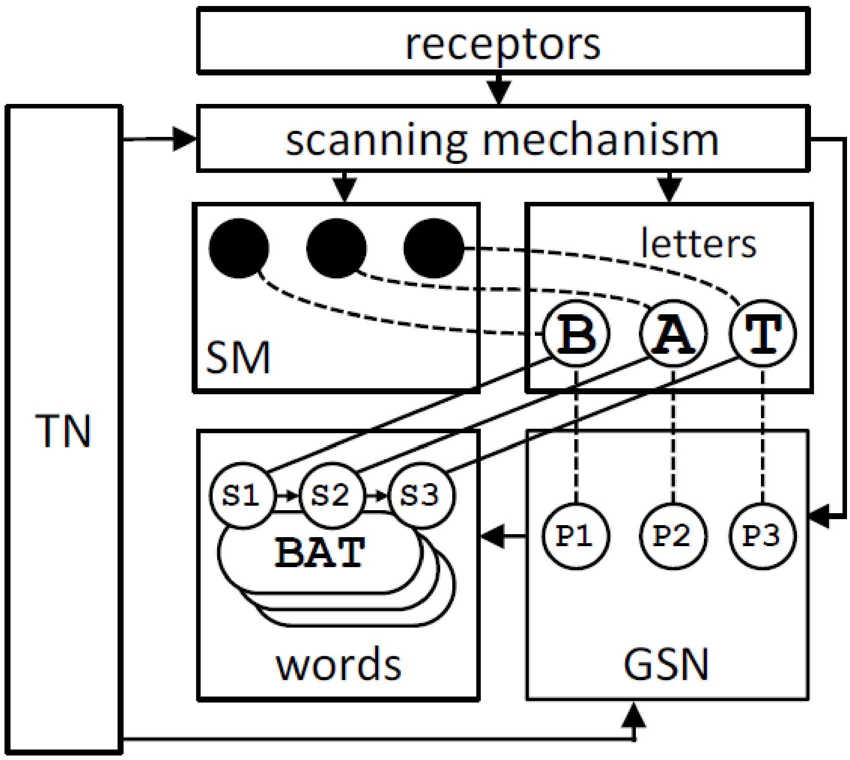

Figure 4: Representation of the letter- and word-recognition process within a conceptual network, rectangles represent modules that process external input (receptors, scanning mechanism), SM represents a spatial map, subnetworks for letter and word identification, a global sequence network (GSN) and a task network (TN) are displayed, arrows and solid lines represent permanent connections through which activation can be passed along, dashed lines represent temporary connections (binding) (de Vries, 2016).

In a conceptual network: cell-assemblies can have different functions, for example some can be activated by a certain letter and others by a certain letter position. The latter are part of the *global sequence network (GSN)*, in Figure 4 representing positions of letters within a word by means of global position nodes. In addition, a local sequence network exists for each word, with the order of the letters of that word represented by local position nodes (comparable to the s1, s2, and s3 nodes in Figure 4) (de Vries, 2016).

If a string of letters is presented to the network, a scanning mechanism transforms the simultaneous input into a sequence of excitations causing the serial, temporary binding of letter nodes and global position nodes. After each binding, each letter node primes all its local position nodes in all word nodes and each global position node primes all local position nodes corresponding to its position. For the example in Figure 4, the first binding causes a coincidence of activation in local position nodes of words starting with the first letter that is processed. The involved word nodes are then activated above baseline but not above critical threshold. After the second binding, activity from the second letter is added to the corresponding word nodes. Finally, when the binding process is completed for all the letters in a word the corresponding word node is activated above critical threshold. Word nodes which become activated by the presented letters but without a complete succession of coincidences of activation in their local sequence nodes, remain in a state of priming. When a lexical decision has to be performed by the network (as is the case in this study), the *task network* (TN) is necessary for monitoring if there is evidence for a word or a non-word. If there is evidence for a non-word (like an illegal letter combination) or not sufficient evidence for a word, a non-word response will be given.

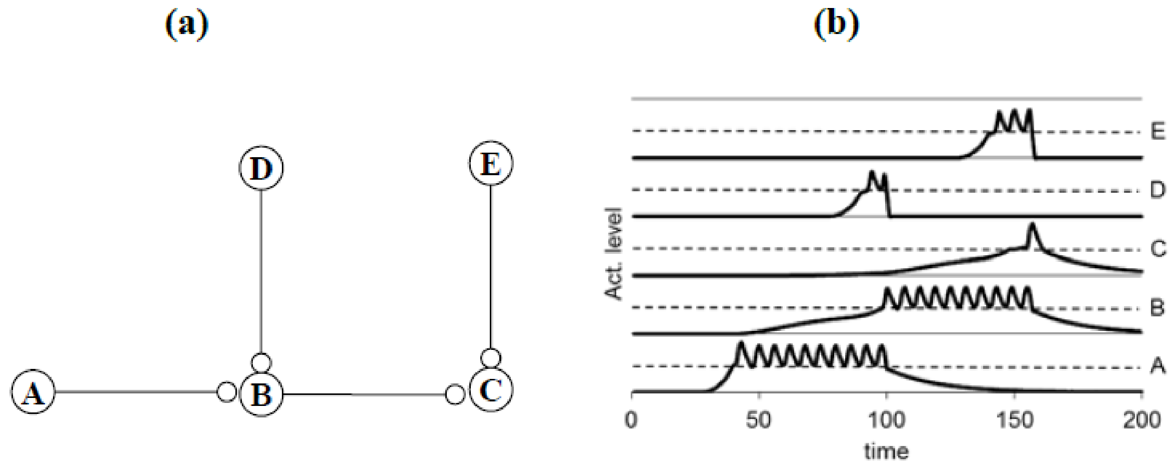

Figure 5 (a) schematic representation of the permanent, bidirectional connections (represented by the lines) between cell-assemblies (represented by the large circles) and subpopulations of neurons of the adjacent cell-assembly (represented by the small circles), (b) representation of the *coincidence of excitation* principle, propagation of excitation from A to B only happens if D is activated at the same time, the dashed lines indicate the critical threshold (de Vries, 2016).

Figure 5 shows a schematic representation of the way in which activation of cell-assemblies is propagated. In Figure 5 (b) it can be seen that ‘A’ is activated first, but ‘B’ is only activated when ‘D’ is activated at the same time as ‘A’. For the network to function as proposed, memory traces of letters must become bound with the representations of their position serially, and not in parallel. If binding of all letters and their positions would take place at the same time this would lead to a massive interference, making it impossible to combine the identity and position correctly (de Vries, 2016).

A conceptual network predicts position dependent, left-to-right effects in primed word recognition based on serial binding (de Vries, 2016). As mentioned earlier: this study used a priming paradigm to analyze the effect of three different prime types on a lexical decision task. The primes consisted of a begin prime (1234(5)dddd), an end prime (dddd5678(9)), and an unrelated prime (dddddddd(d)). Begin primes were expected to have the strongest priming effect because serial binding starts with the first letter of a word. As in the begin prime the first part of the prime and the target word are the same, the target word should already have received quite a lot of activation. The end prime is expected to have a weaker effect because the short presentation of the prime will likely not allow the serial binding process to finish, so pre-activation of the target word will not be as strong. The unrelated prime is not expected to have any effect because the target word will not receive any activation. This priming paradigm is identical to the one used by Zhou (2018). However, this study used German words, instead of Dutch words like the previous two studies, to test whether the hypotheses on binding can be applied to other languages.

Hypotheses

Based on the model explained above, the first hypothesis tested in this study is as follows:

1. *Performance on the lexical decision task will be better for the begin prime followed by unrelated filler letters (e.g., 1234dddd) than for the end prime preceded by unrelated filler letters (e.g., dddd5678) and the unrelated prime (e.g., dddddddd) regarding both accuracy (which will be higher) and reaction time (which will be lower).*

As mentioned during the discussion of previous priming studies, EEG can be a useful tool and can give insight into the level of processing that is reached. Therefore: the second hypothesis is as follows:

2. *The difference between the three priming conditions will be reflected in the ERP signals. The begin prime followed by fillers will be associated with an earlier component, compared to the end prime preceded by fillers and the unrelated prime.*

Lastly, a conceptual network proposes that only words, and not non-words, will activate a memory trace (de Vries, 2016). Therefore, the effect of the primes will only occur when the target is a real word. This leads to the following hypothesis:

3. *The primes will make no difference on performance in the non-word conditions.*

Previous studies

In the previous study by Looden (2016) it was found that for both accuracy and reaction time the begin primes and end primes led to better results (higher accuracy and lower reaction time) than the unrelated primes. Begin and end primes did not differ significantly from each other, however. A significant interaction effect was found between word type (words, non-words) and prime type for both accuracy and reaction time. ERP results for the word condition showed more positivity in the early N250 component in the begin prime condition than in both the end prime and unrelated prime conditions. The latter two did not differ from each other significantly. In the late N250 there was significantly more positivity for both the begin and end prime than the unrelated prime. The begin and end prime conditions were not significantly different. The N400 only showed a significant effect for word type. Both the main effects for word type and prime type on accuracy and reaction time were expected, as was the interaction effect. The lack of a significant difference in both reaction time and accuracy between the begin primes and end primes was surprising, however. The difference in N250 positivity in the word condition was also expected.

The study by Zhou (2018) found no significant effects on accuracy for word type or prime type, nor was there an interaction between the two. There were significant effects for reaction time as reactions in the begin prime condition were fastest, second in the end prime condition, and slowest in the unrelated prime condition. Differences between all three were significant. In the non-word condition only begin prime and unrelated prime differed significantly. The interaction effect between word type and prime type was also significant.

ERP results showed a significant main effect for word type and prime type but no significant interaction in the early N250. In the word condition: begin primes showed more positivity than end primes, which showed more positivity than the unrelated primes. The late N250 again showed main effects for word type and prime type, but no interaction. In the word condition: begin primes showed more positivity than end primes and unrelated primes, the latter two did not differ significantly. The N400 component showed only a main effect for word type with stronger negativity for non-words. The lack of any significant effect for accuracy in the study by Zhou (2018) is quite surprising. The results that were found in reaction time were as expected with differences between begin, end, and unrelated primes; and a significant interaction effect between word type and prime type. The ERP results again showed significantly more positivity in the early N250 as was hypothesized.

Method

Participants

Twenty-four students (9 male, 15 female), all native German speakers, participated in this study. All were in the first year of the bachelor of psychology at the University of Groningen and were between 18 and 30 years old. They were recruited using the Department of Psychology's online subject pool where first year students can sign up for studies in exchange for course credits. All students had normal or corrected-to-normal vision. Furthermore, only people that did not suffer from dyslexia or other neurological conditions were eligible to participate in this study. This study was approved by the Ethical Committee Psychology of the University of Groningen.

Design

A within-subjects design was used for this experiment, consisting of behavioral as well as ERP measurements. The experiment had two conditions which were both presented to all participants: an 8-letter condition in which (non-)words consisted of eight letters, and a 9-

letter condition in which (non-)words consisted of nine letters. Two factors were manipulated in the experiment: word type and prime type. Word type consisted of two levels: words and non-words. Three different prime types were used: a begin-prime, where the first four (in the 8-letter condition) or five (in the 9-letter condition) letters of the prime word were the same as the target word, an end-prime, where the last four or five letters of the prime word were the same as the target word, and an unrelated prime where all letters of the prime were different. Accuracy and reaction time data were analyzed using repeated measures ANOVAs, in cases where sphericity seems violated the Greenhouse-Geisser correction was used.

In this experiment so called *sandwich priming* was used to increase the size of the priming effects. This technique entails presenting a pre-prime: the target word presented ahead of the prime. This should activate relevant word nodes and minimize the activation of nodes that are orthographically related (Lupker & Davis, 2009). Ktori, Grainger, Dufau, and Holcomb (2012) later found that this effect is mediated by the position of the prime. In their study: they found that displaced primes led to smaller ERP priming effects. For that reason, all primes and targets in this experiment were presented in the center of the screen. Minimizing overlap was done by alternating font size instead of stimulus position.

Stimuli

The stimuli consisted of 156 eight-letter German words and 156 nine-letter German words. All words were either nouns or adjectives and were derived from the CELEX Centre for Lexical Information (2001) for two earlier studies. The 8-letter words were used for a study by Prey (2018) and the 9-letter words were used by Brands (2018). All selected words used had a printed frequency of at least 7 per million. The same number of non-words was also used in this experiment, so 156 eight-letter and 156 nine-letter non-words. These were also derived from the same database, and were all pronounceable non-words. Begin and end letters for words and non-words were similar, as to not give away information about the target being either a word or a non-word. Three primes were constructed for every (non-)word to prevent possible bias from using the same prime type for each word every time. For every participant, one of these three primes was randomly selected for each (non-)word. The order of presentation of all (non-)words was then also randomized.

Procedure

Before starting the experiment, participants were asked to read and sign an informed consent form. They were also informed about the use of conducting gel and told that this gel would leave a residue in the hair. Once they had signed the informed consent form: they received written and verbal instructions about the experiment and the setup procedure. The written instruction consisted of a short explanation of the research task, procedure, duration, and compensation. Verbal instructions included mentioning that the electro-gel would be applied using a blunt needle. Participants were informed that participation was strictly voluntarily and they could quit at any time during the experiment without having to state a reason.

Participants were then fitted with an EEG cap with a 10-20 EEG setup. The electrodes used in the measurements were: FP1, FP2, AFz, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, Oz, O2. External electrodes were placed above and below the right eye (VEOGL, VEOGR), on both the left and right temple (HEOGL, HEOGR), and behind both ears on the mastoid bones (A1, A2). The electrodes around the eyes were used to measure eye movement. A1 and A2 were later used as reference electrodes during analysis. During the experiment signals were measured using average reference. Impedance for all electrodes was kept below 10 kΩ.

After the preparation of the EEG cap, participants were taken to the experiment room. Here: they were placed in a darkened, sound proof room in front of the computer monitor at about 50-60cm. They were told the experimenter would be in a monitor room, adjacent to the experimental room, and could hear them through the intercom. The experimenter could also see them via a camera that was connected to a screen in the monitor room, although no video recordings were made. They were given an additional written instruction, asking them to turn off their phone and keep their index fingers on the two outer buttons of an E-prime response box (see appendix for complete instruction). Participants were then verbally instructed to keep their eyes on the center of the screen throughout the experiment and try to be as relaxed as possible, as muscle tension can show up on the EEG recordings. Lastly, participants were told that the experimenter might ask them to wait in between blocks, as electrodes may need adjusting if artefacts are registered. A REFA8 amplifier (Twente Medical Systems International BV) was used. The sampling rate was 500 Hz, with a 170 Hz low-pass filter, and a high-pass filter with a time-constant of 1 sec (0,16 Hz).

Participants were first presented with a practice phase, consisting of two blocks of eight trials, to get familiarized with the task. Reaction time and correct/incorrect feedback was presented after each trial. After the practice trials, participants were asked by the experimenter if everything was clear or if they had any questions. After any questions participants had were answered the researcher would start the first experimental block.

Presentation order of the 8-letter and 9-letter conditions was counterbalanced. Both conditions consisted of four blocks of 158 trials, which included two start up trials at the start of each block to make sure participants were settled and focused. After every block, participants received feedback about their accuracy. Participants could take a break after every block, as the next block would only start if they pressed one of the buttons. Each word or non-word was only presented once to every participant, in randomized order. All stimuli were presented in lower case in font type Courier New bold. E-prime software (version 2.0, Psychology Software Tools Inc., 2016) was used for stimulus presentation and data collection.

The screen resolution was 640x480 pixels, the diagonal of the screen was 56 cm (22”), and the refresh rate was 100 Hz. Every trial, participants were presented with three stimuli in the center of the computer screen. First, a blank screen was shown for a random duration between 500 and 1100ms, which was followed by a mask in the form of a row of hashtags (8 in the 8-letter condition and 9 in the 9-letter condition), shown for 500 ms in font size 20 (95x13 mm). A pre-prime was then presented in font Courier New, size 8 (35x4 mm), for 30ms. The pre-prime was always the same as the target. Next, the condition specific prime was shown for 50ms in Courier New size 12 (30x7 mm). Finally, the target was presented for 80ms in Courier New size 20 (95x10 mm). After target presentation the screen again turned blank for 1480ms, or until the participant responded. As visual changes lead to changes in ERP components, the screen turned blank before the participants responded to prevent interference in the signals that are relevant for analysis. If participants did not respond within those 1480ms a non-response was recorded which was seen as incorrect. Stimuli were presented in different font sizes to minimize their physical overlap. When letters of equal size are presented in quick succession this can lead to a masking effect, perceived letter fusion, or, in the case of identical letters, to facilitation. Participants were not informed beforehand that primes were used in this experiment. Although this is commonly done is priming studies, no fixation was presented in this experiment. This was because in the original sandwich priming study by Lupker and Davis (2010), no type of fixation was mentioned. A schematic representation of the experimental trial sequence is displayed in Figure 6.

The whole experiment took about 30 minutes on average. After the measurements the participants were escorted back to the preparation room where the cap was taken off. They were then debriefed about the actual purpose of the experiment and asked if they noticed the presentation of primes during the experiment.

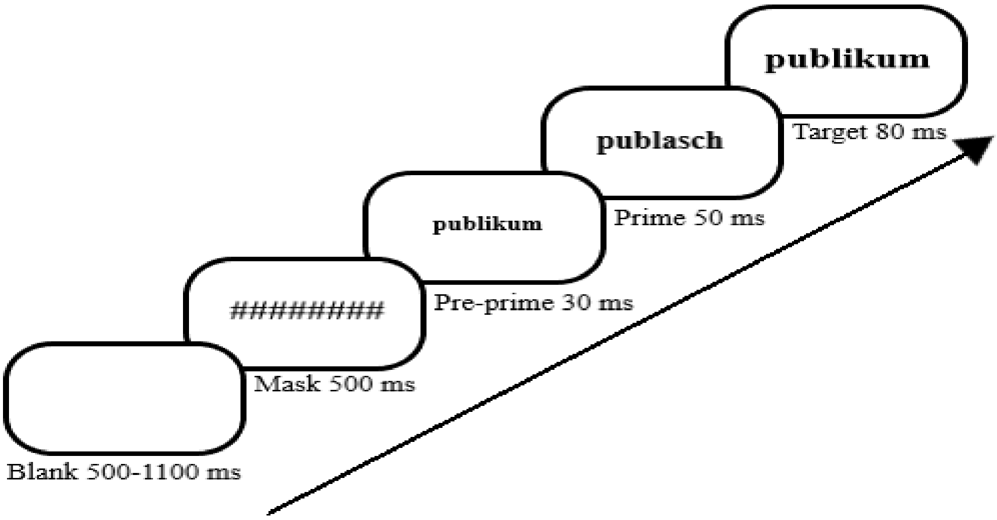

Figure 6*:* Schematic representation of the experimental trial sequence, also showing differences in font size between stimuli (not to scale).

EEG data pre-processing

After data collection, the EEG data was pre-processed before the analysis could take place. Fist, a 50Hz notch-filter was applied to the EOG electrodes to eliminate any interference from the electricity network. The data was then segmented into parts from 200ms before stimulus onset to 1500ms after stimulus onset. The next step was to clear the data of artefacts, which, after a manual inspection of the data, was done in three steps. Step one was a low activity correction, set to automatically remove data where activity was lower than 0.5µV over 100ms. This was done for all channels except the EOG (eye-electrodes) channels. Step two was an automatic max-difference correction on the data for one participant, performed on electrodes C3, F3 and F7 (based on manual inspection). Maximum allowed difference was set to 800µV per 500ms. Step three was a max-difference correction for one participant performed on the A1 electrode (based on the manual inspection). Maximum allowed difference was set to 1500µV per 500ms. Step four was a max-difference correction performed on all participants, on the T8 electrode data. Maximum allowed difference was set to 150µV per 500ms. Large artifacts were found in the FP1 and FP2 electrodes for two participants, so a manual artifact rejection was performed on their data.

The next step was a Gratton & Coles ocular correction using the data from the EOG electrodes. EOG data for one participant was not recorded so a manual rejection of blinks was performed. For three other participants, at least one of the EOG electrodes did not record data properly so the reference electrodes for the ocular rejection had to be adjusted.

Data was then referenced to the average of the two mastoid electrodes. Averages were calculated for each of the six stimulus types (words/non-words x prime type) per participant as well as grand averages over all participants. Based on manual inspection, data from the Cz, Pz, and Fz electrodes was then exported for three intervals: 200ms to 260ms, 260ms to 340ms, and 340ms to 430ms.

Results

Two types of data were collected in this study, namely behavioral data (accuracy and reaction time) and ERP data.

Behavioral data

For both accuracy and reaction time a 2x3 repeated measures ANOVA design was used with word type (words, non-words) and prime type (begin, end, unrelated) as factors. When a significant interaction effect was found, words and non-words were analyzed separately in a one-way repeated measures ANOVA using prime type as a factor. Mauchly's test for sphericity was performed for every analysis but is only reported when the assumption seems violated. Assumptions of normality and homoscedasticity are violated for all performed analyses but repeated measures ANOVAs are robust against violations of these assumptions so no correction was performed.

Accuracy

The 2x3 repeated measures ANOVA for accuracy showed no significant interaction effect ($F(2,46)=.314$, $p=.732$). A significant main effect for word type ($F(1,23)=9.236$, *p*=.006) was found, but not for prime (F(,2,46)=2.880, *p*=.066). The absence of a main effect for prime and an interaction effect is surprising as, based on the literature, a prime effect was expected in the word condition with the best performance in the begin prime trials. Table 1 does show that accuracy is highest in the begin prime trials, although differences are not significant. Only the differences between the word and non-word conditions are significant, with higher accuracy in the word condition.

Table 1: mean accuracy and standard error for the three prime types in the word condition.

Prime type	**Mean accuracy**	**Standard error**
Unrelated	89.9%	1.1%
Begin	91.8%	0.8%
End	90.9%	0.9%

Mean accuracy for all three prime types in the non-word condition are displayed in Table 2. Manual inspection of the table shows that mean accuracy for all prime types are very similar.

Table 2: mean accuracy and standard error for the three prime types in the non-word condition.

Prime type	**Mean accuracy**	**Standard error**
Unrelated	86.2%	1.6%
Begin	87.6%	1.8%
End	86.1%	1.8%

An overview of accuracy in both word conditions and for all prime types can be found in Figure 6.

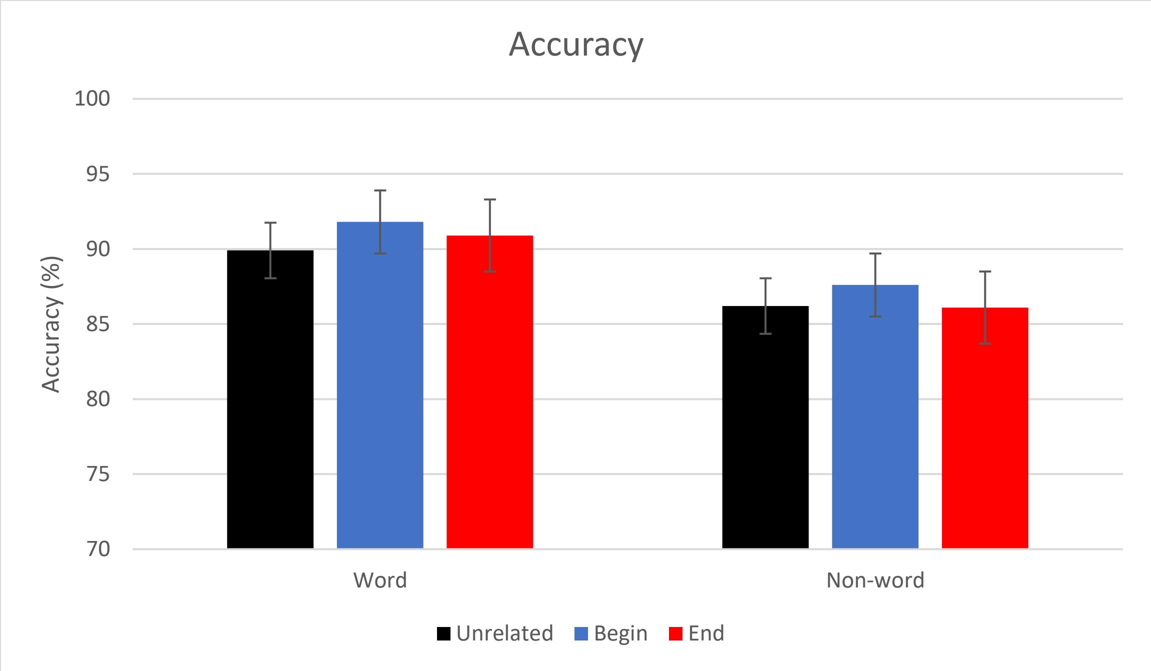

Figure 6: mean accuracy for all three prime types for both the word and non-word condition with error bars showing the 95% confidence interval.

Reaction time

The 2x3 repeated measures ANOVA with word type and prime showed a significant interaction effect ($F(2,46)=4.977$, $p=.011$), a significant effect for word type ($F(1,23)=91.676$, $p<.001$), and prime ($F(2,46)=21.584$, $p<.001$).

As the interaction effect is significant, and because the hypothesis states that primes should not have a significant effect in the non-word condition, words and non-words were analyzed separately. Reaction time in the word condition showed a significant main effect for prime ($F(2,46)=30.986$, $p<.001$). Bonferroni pairwise comparisons show significant differences between all three prime conditions, with $p<.001$ for the unrelated and begin prime; $p=.001$ for the begin and end prime conditions; and $p=.009$ for the unrelated and end prime conditions. Mean reaction times per prime type are displayed in table 3 This shows that the begin prime has the quickest reaction time, followed by the end prime, and the unrelated prime has the slowest reaction time.

Table 3: mean reaction time and standard error for the three prime types in the word condition.

Prime type	**Mean reaction time (ms)**	**Standard error**
Unrelated	512.3	10.0
Begin	492.4	9.6
End	503.8	9.6

No significant main effect for prime type on reaction time is found in the non-word condition ($F(2,46)=2.816$, $p=.070$). Mean reaction time per prime type is displayed in Table 4 This table shows a slight difference between the unrelated and begin prime. Reaction times in the unrelated and end prime conditions seem to be very similar.

Table 4: mean reaction time for the three prime types in the non-word condition

Prime type	**Mean reaction time (ms)**	**Standard error**
Unrelated	557.3	12.6
Begin	549.8	12.4
End	554.7	12.3

An overview of reaction time in both word conditions and for all prime types can be found in Figure 7.

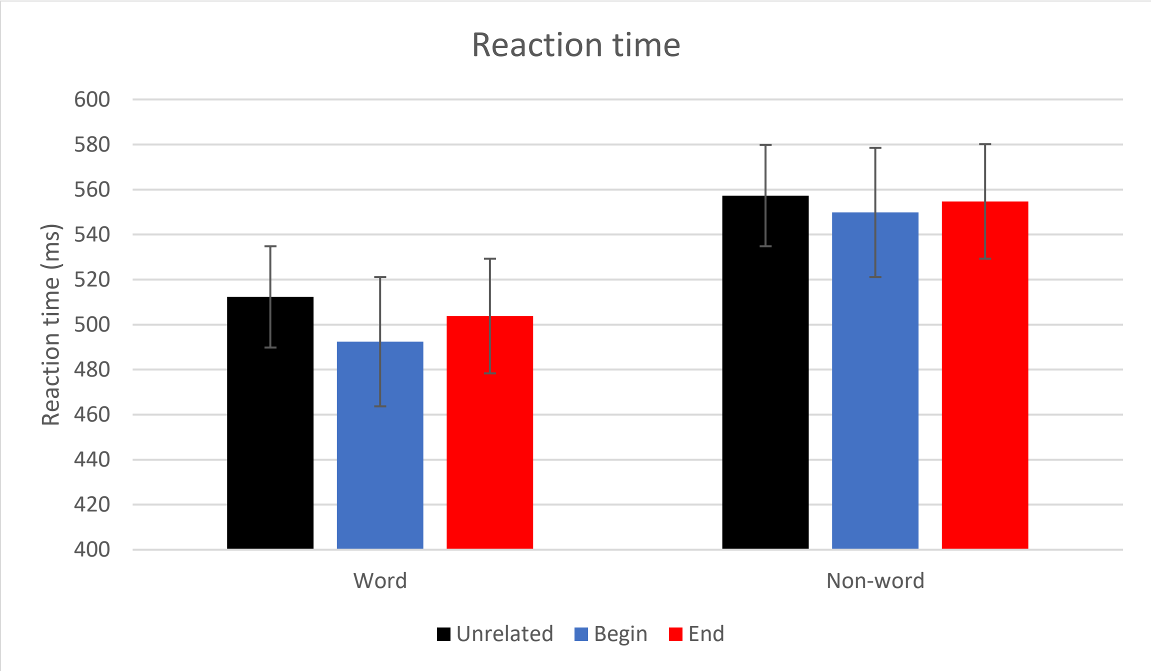

Figure 7: mean reaction times for all three prime types for both the word and non-word condition with error bars showing the 95% confidence interval.

ERP data

The effects of the different prime types on neural activity measured in µV were analyzed by means of a 2x3 repeated measures ANOVA. Separate ANOVAs were performed for all three aforementioned intervals. Average µV from the Fz, Cz, and Pz electrodes was calculated and used for these ANOVAs. The first interval is to analyze the effects in the early N250 components, the second interval is to analyze the effects in the late N250 components, and the last interval is to analyze the effects in the early N400 components.

Figure 8 shows a comparison between begin prime trials and unrelated prime trials in activity across the scalp. It shows that the begin prime trials led to more positivity across the scalp than the unrelated prime trials. The distribution is interesting as priming effects are usually strongest in the occipital region.

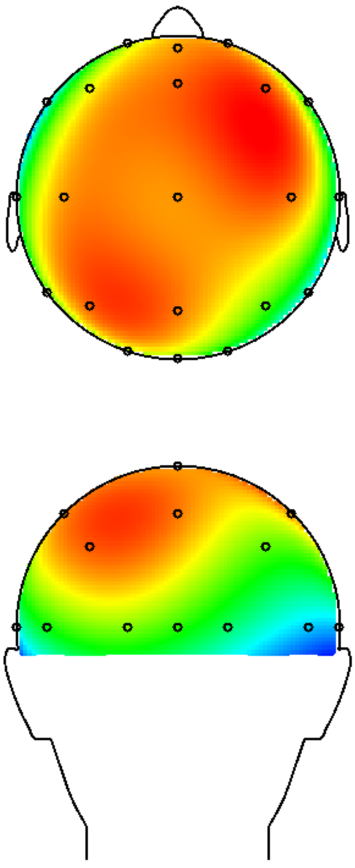

Figure 8: Scalp distribution of activity in begin prime trials compared to unrelated prime trials from 216ms to 484ms after stimulus onset, showing more positivity across the scalp in begin prime trials.

Figure 9 gives an overview of ERP signals in the Pz electrode for all three prime types in the word condition. When looking at the begin prime: it shows a separation from both the end prime and unrelated prime starting at around 200 ms, with the begin prime showing a more positive component. This separation remains clear until around 400 ms, after which the differences between all three prime types seem very small.

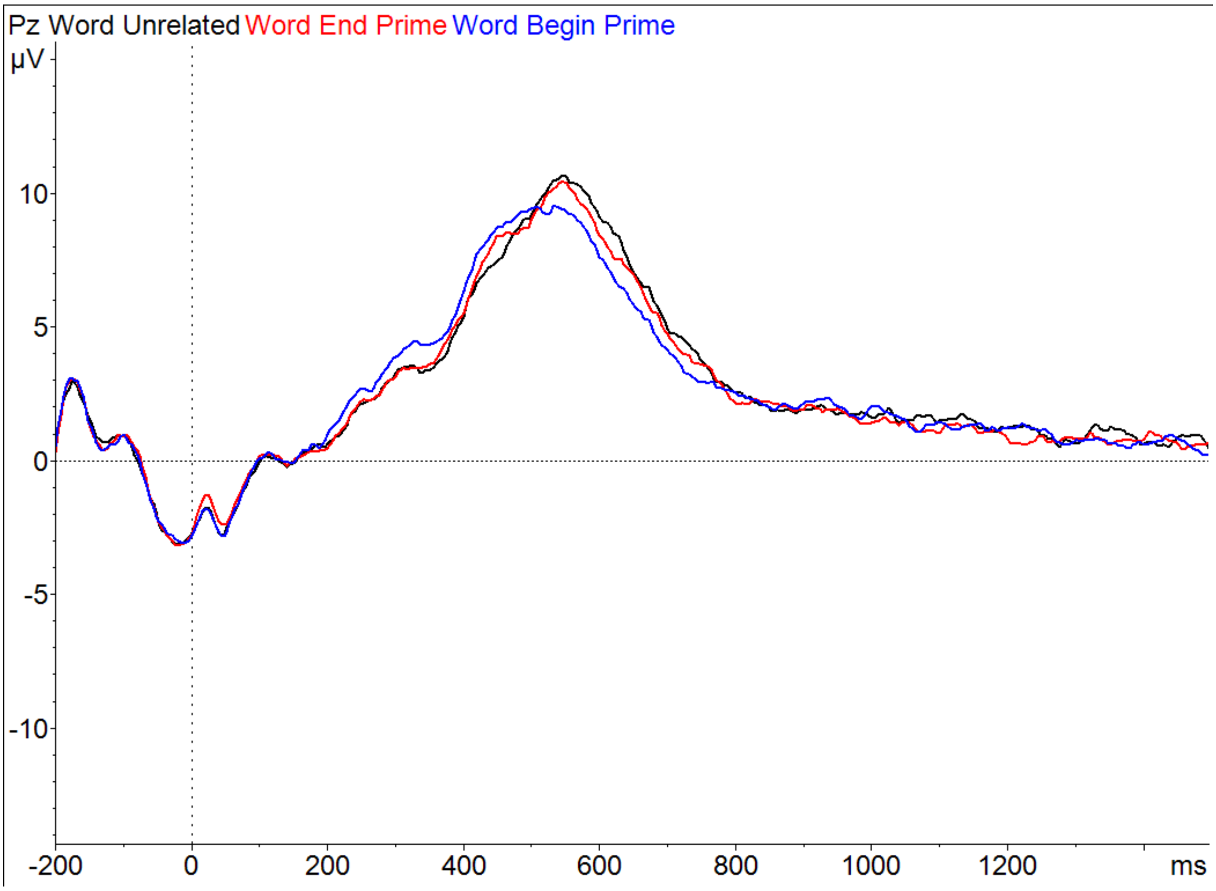

Figure 9: grand average of ERP signal strength in µV in the word condition for unrelated prime (black), begin prime (blue), and end prime (red) trials in the Pz electrode, with positivity plotted up.

Figure 10 shows ERP components for all three prime conditions in the Pz electrode in the non-word condition. This graph shows no clear distinction between any of the three prime types. Moreover, there is a positive component around 200 ms for all three prime types but this is less strong than in the word condition. Both the increase in positivity and the peak of the signal are lower in the non-word condition than in the word condition.

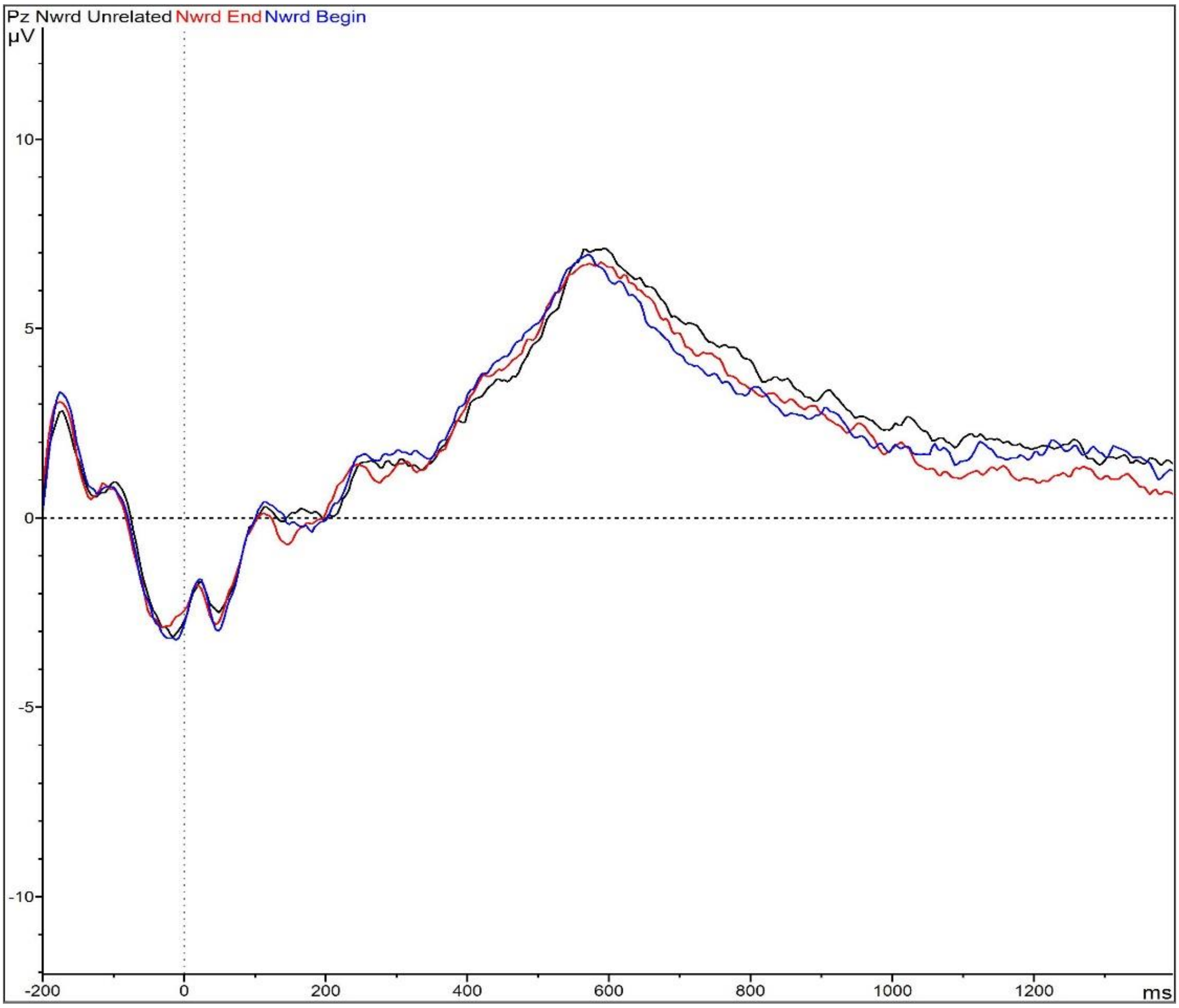

Figure 10: grand average of ERP signal strength in µV in the non-word condition for unrelated prime (black), begin prime (blue), and end prime (red) trials in the Pz electrode, with positivity plotted up.

200ms-260ms

In the 2x3 ANOVA with word type and prime: a significant effect for word type (F(1,23)=49.597, *p*<.001) and prime (F(2,46)=4.580, *p*=.015); but no interaction (F(2,46)=2.770, *p*=.073) was found. LSD pairwise comparison shows significant difference between the unrelated and begin prime (*p*=.006). The unrelated and end prime (*p*=.102) and the begin and end prime (*p*=.218) did not differ significantly. When using the Bonferroni method the difference between unrelated and begin prime remains significant (*p*=.019).

Usually separate analyses are not done when there is no significant interaction effect, however, since behavioral data did show a significant result separate analyses were warranted.

In the word condition: the effect for prime was significant (F(2,46)=5,420, *p*=.008) and Bonferroni pairwise comparisons showed that the difference between unrelated and begin prime was significant (*p*=.025), with begin prime showing more positivity. The difference between the begin and end prime was not significant (*p*=.063), although begin prime did show more positivity. The difference between unrelated prime and end prime (*p*=1.000) was also not significant. When using the LSD method the difference between begin and end prime was significant (*p*=.021) but the difference between unrelated and end prime was not (*p*=.643). In the non-word condition there was no main effect for prime (F(2,46)=2.221, *p*=.120).

Table 5: mean µV and standard errors for the first interval for the three prime types in the word and non-word condition.

	Words		**Non-words**	
Prime type	**Mean µV**	**Standard error**	**Mean µV**	**Standard error**
Unrelated	1.928	0.572	0.963	0.527
Begin	2.555	0.539	1.252	0.487
End	2.014	0.519	1.441	0.533

260ms-340ms

The 2x3 ANOVA for this interval showed significant effects for word type (F(1,23)=97.631, *p*<.001) and prime (F(2,46)=13.585, *p*<.001), but no interaction (F(2,46)=1.752, *p*=.185). LSD pairwise comparison showed significant differences between unrelated and begin primes (*p*=.001), and begin and end primes(*p*<.001); but not between unrelated and end primes (*p*=.303). When using the Bonferroni method, the difference between unrelated and begin prime (*p*=.003) and between begin and end prime (*p*<.001) remain significant.

Once more, because behavioral results did show a significant interaction effect, word condition is analyzed separately. In the word condition: a significant effect for prime was found (F(2,46)=12.708, *p*<.001), with LSD pairwise comparisons showing a significant difference between unrelated and begin prime (*p*=.003), with higher positivity in the begin prime trials. Differences between begin and end prime were also significant (*p*<.001), with again higher positivity in begin prime trials. The difference between unrelated and end prime was not significant (*p*=.294) although positivity was slightly higher in unrelated prime tirals. When using the Bonferroni method the differences between unrelated and begin prime (*p*=.009); and between begin and end prime (*p*<.001) remained significant. In the non-word condition there was no significant effect for prime (F(2,46)=2.658, *p*=.081),

Table 6: mean µV and standard errors for the second interval for the three prime types in the word and non-word condition.

	Words		**Non-words**	
Prime type	**Mean µV**	**Standard error**	**Mean µV**	**Standard error**
Unrelated	1.974	0.523	-0.128	0.526
Begin	2.754	0.533	0.234	0.533
End	1.758	0.493	-0.230	0.561

340ms-420ms

In the 2x3 ANOVA: significant effects were found for word type (F(1,23)=88.353, *p*<.001) and prime (F(2,46)=3.689, *p*=.033). No interaction between the two was again found (F(2,46)=.677, *p*=.513). LSD pairwise comparison shows that unrelated and begin prime differ significantly (*p*=.022). Differences between unrelated and end prime (*p*=.728) and begin and end prime (*p*=.053) were not significant. When using the Bonferroni method the difference between unrelated and end prime (*p*=.067) was no longer significant. Based on the significant interaction effect found in the behavioral data, separate analyses were again performed for words and non-words.

The word condition in the third interval showed a significant main effect for prime (F(2,46)=3.809, *p*=.029). LSD pairwise comparisons showed a significant difference between unrelated and begin prime (*p*=.031) Differences between begin and end prime (*p*=.055), and unrelated and end prime (*p*=.502) were not significant. When using the Bonferroni method the difference between begin and end prime is no longer significant (*p*=.092). The non-word condition did not show a significant main effect for prime (F(2,46)=.673, *p*=.515).

Table 7: mean µV and standard errors for the third interval for the three prime types in the word and non-word condition.

	Words		**Non-words**	
Prime type	**Mean µV**	**Standard error**	**Mean µV**	**Standard error**
Unrelated	3.452	0.523	0.583	.443
Begin	4.116	0.478	0.830	.434
End	3.593	0.502	0.559	.427

Discussion

Hypotheses

Looking back at the hypotheses we can see that the results were quite nicely in line with the expectations. The first hypothesis that was tested was: *The reaction time for the begin prime followed by unrelated filler letters (e.g., 1234dddd) will be lower than that for the end prime preceded by unrelated filler letters (e.g., dddd5678) and the unrelated prime (e.g., dddddddd).*

Reaction time in the word condition shows that reactions in the begin prime condition are fastest, followed by the end prime condition, and lastly in the unrelated prime condition. The difference between the begin prime and end prime is quite interesting, as the study by Zhou (2018) also found this effect, but the study by Looden (2016) didn’t. The effect can be explained by a conceptual network, however. As previously mentioned, the study by Looden (2016) did not use distractor letters in the primes, as opposed to this study and the study by Zhou (2018). Therefore, in the study by Looden (2016), the serial binding process did not have any interference from distractor letters that had to be processed first. This could explain why the effects of begin primes and end primes were equally strong in the study by Looden (2016). In both this study and the one by Zhou (2018), distractor letters likely caused interference and made for weaker facilitation than begin primes. What is interesting in this, is that letter identity information is not bound to the correct letter position information in end prime trials in the study by Looden (2016), as the first presented letter in the end prime corresponds with the fifth letter in the target word. However, prime 5678(9) will excite all local position nodes of local sequence networks of words that contain the same letters. This will thus include the fifth local position node in the LSN of the target word. The same applies to the following letters in the prime which will lead to a buildup in excitation in the LSN of the target’s word node. This will result in the priming of the target word. Importantly, the last letter of its LSN contributes more than the previous letters because this signals the finalization of the binding process. Since the last letter is included in the prime, this will enhance the priming effect (de Vries, 2016).

A similar left-to-right principle is used in the SERIOL model (Whitney, 2001), however, this model is not based on a general mechanism for binding necessary for the integration of location, identity, and position. Contrary to many of the models explained in the introduction (e.g. IA model (McClelland & Rumelhart, 1981), overlap model (Gomez et al., 2008)), the SERIOL model does assume left-to-right serial processing and could thus potentially explain the increased priming effect for begin primes.

Accuracy results were not as clear as the results in reaction time. No main effect was found for prime on accuracy, nor was there an interaction between prime and word type. Only the difference between words and non-words was significant, with higher accuracy in the word condition. The lack of a main effect for prime was quite surprising, but it might have to do with the high overall accuracy rate. Overall: accuracy in the word condition was around 90% so that leaves very little room for improvement. The study by Zhou (2018) also did not find a significant effect of priming on accuracy. However, the study by Looden (2016) did find that both begin prime trials and end prime trials showed significantly higher accuracy than unrelated prime trials, even though average accuracy was even higher in the study by Looden (2016), than in this study or the one by Zhou (2018).

These differences could again have to do with differences in the priming paradigm used by Looden (2016). Possibly, the addition of distractor letters to the begin and end primes has reduced the priming effects by causing interference in the local sequence network of the target words (de Vries, 2016). This could lead to slightly reduced facilitation. Seeing as accuracy was already quite high in both this study and the study by Zhou (2018), it could be that only a strong priming effect could cause accuracy to increase significantly.

The second hypothesis regarded the ERP results: *The difference between the three priming conditions will be reflected in the ERP signals. The begin prime followed by fillers will be associated with an earlier component, compared to the end prime preceded by fillers and the unrelated prime.*

When looking at the ERP results it can be seen that in the word condition: an early separation between begin prime and the other two prime conditions was detected in the early N250 window. According to a conceptual network this is caused by the successive pre-activation of the target word by the nodes first letters. The word node is then in a state of priming. When the target word is then presented, its excitation will reach critical threshold more quickly. This is reflected in the ERP signals, leading to an earlier component. The SERIOL model (Whitney, 2001) would likely predict similar results as the serial activation is more strongly facilitated by the begin primes. Furthermore the model states that the first letter receives the most activation and the last letter the least, this could explain the stronger and earlier positive component found in begin prime trials.

When including word trials in the other two intervals: it was found that begin prime differed significantly from both unrelated and end prime, but unrelated and end prime did not differ significantly. It can be seen that there is a larger positive peak in begin prime trials, starting around 200ms and this separation remains clear until around 400ms. This, along with the lower reaction times for begin primes, indeed suggests pre-activation of the word nodes as proposed by a conceptual network.

The third and last hypothesis stated that: *The primes will make no difference on performance in the non-word condition.* For both accuracy and reaction time this was true in this study. No main effect for prime was found on either accuracy or reaction time in the non-word condition. As differences in performance were expected in the word condition but not the non-word condition, an interaction effect would be expected. For accuracy this was not found. This *was* found for reaction time, where reaction time was significantly lower in the word condition. The studies by Looden (2016) and Zhou (2018) also reported lower reaction times in the word condition. This suggests that words are identified quicker than non-words, suggesting that the word identification process takes place first. When there is not enough evidence that the target is a word, the TN in a conceptual network will produce a non-word response.

Implications

As previously mentioned in the hypotheses section: results from this study are largely in line with the hypotheses. This suggests that a conceptual network quite accurately predicted the results found in the experiment. However, as mentioned earlier, another model could possibly explain the results as well: the SERIOL model by Whitney (2001). This model also proposes left to right processes, and states that this takes place by decreasing activity from the first letter to the last. So the first letter gets the strongest activation, followed by the second, and so on. This would theoretically lead to similar results in the current priming paradigm. It could also possibly explain the early ERP component found in begin prime trials, as begin prime trials lead to the strongest priming and thus lead to a quicker positive components when the letters that are in a state of priming receive activation again.

It is questionable if this model could explain the priming effect found in end prime trials. As the last letters of a word receive little activation according to this model, and the prime is presented for such a short time that it is questionable if the last letters of a word would receive enough activation to cause a significant priming effect. What is even more important, however, is the difference between the word and non-word condition. A conceptual network states that non-words do not activate memory trails and thus are unlikely to receive significant priming. This study found no significant priming effects in the non-word condition. The SERIOL model does not make this distinction and could not explain the differences in priming effects between words and non-words. It seems therefore that the theory proposed in a conceptual network is the most likely explanation for the results.

For further comparison between these two models, a priming paradigm could be constructed using primes similar to the end primes used in this study. The SERIOL model (Whitney, 2001) proposes serial processing and states that the amount of activation decreases from letter to the next. A conceptual network (de Vries, 2016) proposes a serial binding process but allows the local sequence network of a word to ‘catch up’ with an end prime because it proposes that every activated letter node will excite every local position node of a local sequence network that contains the right letters. This means that the strength of the priming effect decreases faster according to the SERIOL model than according to a conceptual network when relevant letters are preceded by more and more distractor letters. The proposed priming paradigm would feature a prime consisting one relevant letter and around 10 distractor letters. The position of the relevant letter can then vary from fifth to tenth position. A target is then presented consisting of a (non-)word with the relevant letter at the same position. The screen will then turn blank and participants will be shown an arrow pointing to where the relevant letter was presented. They will then have to reproduce the letter. According to the SERIOL model: the priming effect should decrease strongly but quite gradually the further the target letter is presented, as the amount of activation decreases from letter to letter. According to a conceptual network a later but more abrupt decrease in priming effect would be expected, as activation does not decrease from letter to letter but due to the serial binding process later letters might not be bound in time to be activated.

Quite interestingly, significant differences between the 8- and 9-letter condition were found in this study. Performance for both accuracy and reaction time was better in the 9-letter word condition. This seems counterintuitive as longer words should be more difficult to process because of the increased length of the binding process (de Vries, 2016).

Improvements in performance could have to do with the additional information received by the primes in the 9-letter word condition as they consisted of five identical letters instead of four. However, there was no evidence for an increased priming effect in the 9-letter word condition. So perhaps the words and non-words in the 8-letter condition were more difficult to distinguish from each other. Differences between words of different lengths in orthographic processing could be interesting for future research.

Reviewing previous literature

In the introduction of this paper, many previous studies involving priming have been discussed. Those papers used variations to the IA model to explain the findings, all of them assuming parallel letter processing. Could these findings also be explained by a conceptual network?

The first study discussed is one by Humphreys, Evett, and Quinlan (1990) and found that words can be primed by orthographically related non-words. Five letter words were primed by four letter non-words and it was found that the strength of the priming effect increased when the overlap of letter identity and position between prime and target increased. This is consistent with a conceptual network, as more letter nodes are temporarily bound to the correct local position nodes and the corresponding word node would receive more excitation. As mentioned before, however, all local position nodes in the local sequence network that contain corresponding letters will receive excitation. This would explain the presence of a priming effect, however small, when letters in the prime are transposed.

Grainger and Holcomb (2009) found differences in ERP components when using different types of subset primes, with hyphenated primes (c-lle-t for COLLECT) leading to an earlier N250 component than concatenated primes (cllet for COLLECT). In the context of a conceptual network: this could suggest that the difference in ERP components in the hyphenated condition has to do with facilitation of the serial binding process. By inserting hyphens the absolute position of the letters remains intact, facilitating the left-to-right serial binding of letter identity and position.

Ktori, Midgley, Holcomb and Grainger (2014) studied the priming effects of superset primes and found that hyphen inserted primes (ma-rk-et for MARKET) led to stronger priming effects than letter inserted primes (maurkdet for MARKET). Looking from the perspective of a conceptual network the decreased priming effect caused by letter inserted superset primes could be explained by interference in the serial binding process. Binding will likely take place for the inserted letters but not for hyphens, so binding would take longer in the letter-insert condition. This interference is then likely amplified by the activation of irrelevant letter nodes.

Marzouki, Meeter & Grainger (2013) researched the effect of variations in the location of target presentation on the screen. A significant priming effect was found even when target location varied horizontally relative to the prime location. A conceptual network could also explain these results: as mentioned before the model proposes a solution for the integration (binding) of letter identity, position, and location information. In this case, the letter identity and position information would already be bound. Letter identity and relative position is unchanged so this binding remains intact, only letter location varies as the target word is presented at a different location on the screen. As the binding of letter identity and position has already taken place and is unchanged, it is expected to facilitate the recognition of the same word at a different location.

Massol, Grainger, Midgley, and Holcomb (2012) found that pronounceable non-words led to stronger priming effects than non-words made up of consonant strings. A conceptual network would explain this by stating that pronounceable non-words are more similar to real words and will thus lead to (more) excitation of existing memory traces. This will lead to higher overall activation in letter, location, and word nodes, making the priming effect stronger.

Meade et al. (2018) demonstrated that priming words with close orthographic neighbor words led to slower reactions and a stronger reversed N400 effect. This was explained by the lateral inhibition proposed by the IA model: activation of a word detector leads to inhibition of neighboring word detectors (Meade et al., 2018). This effect was only found for words with a high number of orthographic neighbors and with participants who scored high on spelling. This could be explained within the theory of a conceptual network: participants who score higher on spelling would likely have stronger memory traces for each word node as they are better trained at reading. They will also likely be better at making distinctions between different words that are similar. This would likely lead to more excitation in the word node corresponding to the prime, and (relatively) less excitation in orthographic neighbor word nodes. This could explain the increased reaction time in the lexical decision task.

Grainger and Beyersmann (2017) found that when a target word is primed by a word with the target embedded (scandal for scan) it typically leads to inhibition or a null effect, while a non-word prime with the target embedded (scanald for scan) leads to facilitation. This can again be explained by the inhibition mechanism as proposed by the IA. It could also be explained within the confounds of a conceptual network by stating that when presenting the prime (e.g. scandal for scan) binding has already taken place beyond the letter ‘n’, thus activating memory traces for words with more letters than ‘scan’. In the case of the non-words (e.g. scanald for scan) the binding of letters beyond the ‘n’ would not activate any additional memory traces as no such words exist. This could mean that the word node for ‘scan’ remains the word node that receives the most excitation. Which could explain why no interference is found when non-word primes are used.

Limitations

The biggest limitation for this study was probably the lack of a significant main effect on accuracy. Contrary to the study by Looden (2016) this study found no effect (and neither did the study by Zhou (2018)). This could have to do with the high overall accuracy of around 90%. This could be fixed by making the task more difficult for participants, for example by making target words longer or harder to distinguish from non-words. By increasing task difficulty, the participants will have to rely more heavily on the information that is given to them by the primes.

Also important to note is that, as mentioned above, there are some inconsistencies between this study, the study by Looden (2016), and the study by Zhou (2018). Exact replication of results would be expected based on the high similarities in experimental paradigms, especially between this study and the study by Zhou (2018). This is not entirely true, however.

Firstly, the study by Looden (2016) *did* find a priming effect on accuracy where both other studies did not. This could have to do with the difference between the primes that were used, as the study by Looden (2016) was the only one that did not use distractor letters. Looden (2016) also did not find a significant priming effect in the ERP results for the third interval (which was 375 ms to 425 ms, as opposed to 340 ms to 420 ms in this study) whereas this study did find a significant effect for prime. Furthermore, Looden (2016) only analyzed the Cz electrode where this study took the average of the Fz, Cz, and Pz electrodes.

There were also some differences between this study and the study by Zhou (2018). Firstly, the study by Zhou (2018) found a significant main effect for priming on reaction time in the non-word condition. It was found that the reaction time for begin prime trials was lower than both unrelated and end prime trials (Zhou, 2018). This study did not find any priming effect in the non-word condition. The priming effect in itself can be explained, as it could have to do with the use of illegal letter combinations in the begin primes. This could provide evidence to the task network for a non-word, nudging it towards a non-word response. When the same illegal letter combination is then presented in the target word, a non-word response could then be given more quickly. The inconsistency in the presence of this effect is quite strange, however. Perhaps non-word begin primes in this study contained fewer illegal letter combinations than the non-word begin primes used by Zhou (2018), as German and Dutch language use different letter combinations. Interestingly, separate analysis of the 8- and 9-letter conditions showed that a significant priming effect on non-words was found in the 8-letter condition in this study, but not in the 9-letter condition. Reaction time in the 8-letter non-word condition was significantly lower in begin prime trials than in both unrelated and end prime trials (which did not differ from each other significantly). Facilitating non-word responses using illegal letter combinations in begin prime trials could be an interesting topic for future research.

Furthermore, there were some differences in ERP results between this study and the study by Zhou (2018). Different electrodes were analyzed in both studies, as Zhou (2018) analyzed the AFz and Pz electrodes (with different intervals for both), and this study analyzed the averages for the Fz, Cz, and Pz electrodes. Selection of the electrodes was done manually and based on the visual differences in ERP components found in the different electrodes. In the first interval: Zhou (2018) found a significant interaction effect as well as a main effect for prime in the non-word condition, where this study found neither of those effects. In the second interval: Zhou (2018) found a main effect for priming in the non-word condition where this study did not. In the third interval: Zhou (2018) only mentioned a main effect for word type, where this study also found a significant main effect for priming in the word condition. The significant priming effect found by Zhou (2018) in the non-word condition could correspond with the significant priming effect that study found on reaction time.

One final possible limitation is the lack of a fixation cross in the experiment. As mentioned in the method section: there was no fixation cross included in the experiment because there was no mention of this in the original sandwich priming study by Lupker and Davis (2010). This could, however, possibly have strengthened or caused the left-to-right effect. When the mask is presented, it is possible that participants will fixate on the left side of the mask, because that is where reading starts. This could then lead to a strengthened priming effect for the begin primes, because the relevant information is then presented on the side of fixation. Future research can control for this by including a fixation cross in the center of the screen before presentation of the mask.

References

Andrews, S. (1989). Frequency and neighborhood size effects on lexical access: Activation or search? Journal of Experimental Psychology: Learning, Memory, and Cognition, 15, 802–814.

Brands, T., (2018). The Serial Nature of Word Recognition – A Structural Account (bachelor thesis). Available from: https://gmw.studenttheses.ub.rug.nl/.

Cheng, H. (2007). *Word superiority effect - Wikipedia*. [Illustration]. Retrieved July 10, 2019 from https://en.wikipedia.org/wiki/Word_superiority_effect

De Vries, P. H. (2016). Neural binding in letter- and word-recognition. In K. E. Twomey, A. Smith, G. Westermann, & P. Monaghan (Eds.), *Neurocomputational models of cognitive development and processing: Proceedings of the 14th neural computation and psychology workshop* (pp. 17–33). New Jersey, USA: World Scientific.

Dufau, S., Grainger, J., & Holcomb, P. J. (2008). An ERP investigation of location invariance in masked repetition priming. *Cognitive, Affective, & Behavioral Neuroscience*, *8*(2), 222–228. https://doi.org/10.3758/cabn.8.2.222

Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review*, *115*(3), 577–600. https://doi.org/10.1037/a0012667

Grainger, J. (2008). Cracking the orthographic code: An introduction. *Language and Cognitive Processes*, *23*(1), 1–35. https://doi.org/10.1080/01690960701578013

Grainger, J. (2018). Orthographic processing: A ‘mid-level’ vision of reading: The 44th Sir Frederic Bartlett Lecture. *Quarterly Journal of Experimental Psychology*, *71*(2), 335–359. https://doi.org/10.1080/17470218.2017.1314515

Grainger, J., Beyersmann, E. (2017). Edge-aligned embedded word activation initiates morpho-orthographic segmentation. In Ross, B. (Ed.), Psychology of Learning and Motivation, 67, 285–317.

Grainger, J., & Holcomb, P. J. (2009). An ERP investigation of orthographic priming with relative-position and absolute-position primes. *Brain Research*, *1270*, 45–53. Retrieved from https://www-clinicalkey-com.proxy-ub.rug.nl/#!/content/playContent/1-s2.0-S0006899309004648

Grainger J., Van Heuven W. (2003): Modeling letter position coding in printed word perception. In Bonin P. (eds): The Mental Lexicon. New York: Nova Science Publishers, 2003. pp. 1-24

Humphreys, G. W., Evett, L. J., Quinlan, P. T. (1990). Orthographic processing in visual word identification. Cognitive Psychology, 22, 517–560.

Ktori, M., Grainger, J., Dufau, S., & Holcomb, P. J. (2012). The “electrophysiological sandwich”: A method for amplifying ERP priming effects. *Psychophysiology*, , 1114–1124. https://doi.org/10.1111/j.1469-8986.2012.01387.x

Ktori, M., Midgley, K., Holcomb, P. J., & Grainger, J. (2014). An ERP investigation of orthographic priming with superset primes. *Brain Research*, *1594*, 233–244. Retrieved from https://www-clinicalkey-com.proxy-ub.rug.nl/#!/content/playContent/1-s2.0-S0006899314014656

Looden, T. (2016). *Visual word recognition and serial binding: an ERP study* (bachelor thesis). Available from: https://gmw.studenttheses.ub.rug.nl/.

Lupker, S.J., & Davis, C.J. (2009). Sandwich priming: A method for overcoming the limitations of masked priming by reducing lexical competitor effects. Journal of Experimental Psychology. *Learning, Memory, and Cognition*, *35*(3), 618-39. doi:10.1037/a0015278

Marzouki, Y., Meeter, M., & Grainger, J. (2013). Location invariance in masked repetition priming of letters and words. *Acta Psychologica*, *142*(1), 23–29. https://doi.org/10.1016/j.actpsy.2012.10.006

Massol, S., Grainger, J., Midgley, K. J., & Holcomb, P. J. (2012). Masked repetition priming of letter-in-string identification: An ERP investigation. *Brain Research*, *1472*, 74–88. https://doi.org/10.1016/j.brainres.2012.07.018

McClelland, J. L., & Rumelhart, D. E. (1981). An Interactive Activation Model of Context Effects in Letter Perception: Part 1. An Account of Basic Findings. *Psychological Review*, *88*(5), 375–407. Retrieved from http://web.b.ebscohost.com.proxy-ub.rug.nl/ehost/pdfviewer/pdfviewer?vid=11&sid=b05ccae1-d997-429c-8b51-b413e19a5546%40pdc-v-sessmgr03

Meade, G., Grainger, J., Midgley, K. J., Emmorey, K., & Holcomb, P. J. (2018). From sublexical facilitation to lexical competition: ERP effects of masked neighbor priming. *Brain Research*, *1685*, 29–41. https://doi.org/10.1016/j.brainres.2018.01.029

No title. (n.d.). [Illustration]. Retrieved from https://dogsbody.psych.mun.ca/_notes/3450/Chapter%203.pdf

Prey, A. (2018). Word-Recognition as a Result of Serial Binding: Effects of Begin- and End Primes (bachelor thesis). Available from: https://gmw.studenttheses.ub.rug.nl/.

Psychology Software Tools, Inc. [E-Prime 3.0]. (2016). Retrieved June 2, 2019 from

http://www.pstnet.com.

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin and Review*, *8*(2), 221–243. Retrieved from https://link-springer-com.proxy-ub.rug.nl/content/pdf/10.3758%2FBF03196158.pdf

Zhou, X. (2018). *The role of a serial binding process in visual word-recognition: an ERP study* (master's thesis). Available from: https://gmw.studenttheses.ub.rug.nl/.

Appendix

1. **Participant information**

university of groningen / faculty of behavioural and social sciences / psychology

RESEARCH INFORMATION

(for participants, to take home)

“18073-SP: **Test your knowledge of German words”**

- **Researchers**

Robin van Grieken, Master student at the University of Groningen

Pieter de Vries, Experimental Psychology

Berry Wijers, Experimental Psychology

- **Contact information**

Robin van Grieken

r.van.grieken@student.rug.nl

0610395124

- **Introduction**

You are invited to take part in a research study of …

German word recognition.

We are asking you to take part because …

You are a native German speaker and we are interested in the processes that are involved in the recognition of German words.

Please read this information sheet carefully and ask any questions you may have before consenting to take part in the study.

- **Purpose of the research**

The purpose of this research is to examine the processes that take place in the brain when it is processing written words.

- **Summary of the research**

You will be given a computer task where words and non-words will be shown on the screen, it will be your job to answer as quickly as possible if a stimulus is a word or a non-word. While performing this task you will be fitted with an EEG cap.

- **Detailed research procedures**

If you agree to participate in this study, we will ask you to …

First read and sign an informed consent form, this is standard procedure in scientific research. Then you will be fitted with an EEG cap, and four additional electrodes that will be placed around the eyes. The electrodes will be filled with conductive gel, which will leave a bit of residue after the experiment.

We will then proceed to another room where the experiment is set up. You will be placed in front of a computer screen and the EEG cap will be connected. The computer task involving word recognition will then start. Precise instructions will follow. The task will involve words and non-words consisting of eight or nine letters. Your task will be to identify as quickly as possible if a stimulus is a word or a non-word.

The computer task will take about 30 minutes. After that, the EEG cap will be disconnected from the computer and we will return to this room for the debriefing. You can then receive additional information about the experiment.

- **Duration of the research**

In total, the experiment will take a maximum of two and a half hours, this includes the preparation of the EEG cap.

- **Risks**

"We do not anticipate any risk to you participating in this study."

- **Benefits**

This research will provide more insight into the processes behind written word recognition in the brain. It can help us understand how words and ultimately other information is identified and processed.

- **Compensation**

For participating in this study, you will receive 3.1 SONA credits.

- **Your privacy**

The data that will be collected during this study will be treated confidentially. Your data will only be processed using a code number. This code number is not linked to personal information that might be used to directly identify you, such as your name and e-mail address.

Your research data will be analysed by the researchers. Research data that are published, for example in scientific journals, cannot identify you.

Fully anonymised research data may be shared with other researchers for scientific purposes. Your personal information will remain confidential and will not be shared with third parties without your explicit consent. Your other research data will only be shared if they cannot be used to identify you. Hence your privacy is guaranteed.

- **Participation is voluntary**

Participating in the research is completely voluntary. It is your choice whether to participate or not. At any time you may withdraw from the research study, without having to provide a reason. Stopping to participate will not have consequences for you in any way.

You can also ask for your data to be removed from the research database.

- **Further information**

Questions about the research may be asked to the researchers now, and at all times during the research. If you have questions about the research afterwards, you may contact the researchers via e-mail or phone.

If you have any questions or concerns regarding your rights as a research participant, you may contact the Ethics Committee of the Department of Psychology of the University of Groningen, to be reached via ecp@rug.nl. **You will be given a copy of this form to keep for your records.**

2. Informed consent form

university of groningen / faculty of behavioural and social sciences / psychology

Title of the study

18073-SP Test your knowledge of German words, an EEG study

INFORMED CONSENT

(for mentally competent persons aged 12 years and older)

I have read the research information, together with one of the researchers.

I have had the opportunity to ask questions about the study, and any questions that I have asked have been answered to my satisfaction.

I have had sufficient time to decide whether or not to participate.

☐ I consent voluntarily to participate in this study.

- ☐ In addition, I consent voluntarily to my data being used for the purposes mentioned in the research information sheet. My privacy is guaranteed at all times.

If I decide to stop participating, I do not need to provide a reason. When I stop, I will be given the opportunity to have all my data removed from the database.

NAMES AND SIGNATURES

Full name of participant:	Signature:	Date:
Name of researcher present:	Signature:	Date:

The researcher present declares that the participant was informed about the study verbally and in writing.

3. Written instructions

Instructions

Welcome!

Please, turn of your cell phone.

In all trials of the experiments, a row of hashtags (#) will be displayed followed by a sequence of letters. For each of these sequences, you must decide if they form an existing German word or no:

Pressing the right button = existing word

Pressing the left button = non-word

During the experiment, please keep your index fingers on these buttons and direct your attention to the middle of the row of hashtags.

In each trial you have one and a half second to respond.

Before the experiment begins, you will be presented with two practice blocks.

Press the right or the left button to continue…

AFTER THE PRACTICE TRIALS

The experiment consists of two parts with words of different lengths.

You either start with eight-letter words in part 1 and nine-letter words in part 2, or the other way around.

Each part has four blocks

Press the right or the left button to continue…

4. Debriefing

rijksuniversiteit groningen / faculteit gedrags- en maatschappijwetenschappen / psychologie

Debriefing of Human Participants Research

“Test your knowledge of German words”

Thank you for participating in this study! By your participation, we hopefully made progress in our understanding of visual word processing.

Actual purpose of the research

The main purpose of this research was to examine the differences between three, virtually invisible prime types in behavior (reaction time and accuracy) and ERP signals (brain activity). There was a begin prime, where the first four or five letters of the prime were the same as the target. An end prime, where the last four or five letters of the prime were the same as the target. And there was an unrelated prime where all letters were different.

This data we will foster the development of a model of cognitive brain functioning explaining visual word recognition. For example, information about the identity of a letter, its location, and position is thought to be processed separately, but this information has to be combined at some point to process a written word.

Actual research question and expectations

Three different hypotheses are tested in this research:

1. The reaction time for the begin prime followed by unrelated filler letters (e.g., 1234dddd) will be lower than that for the end prime preceded by unrelated filler letters (e.g., dddd5678) and the unrelated prime (e.g., dddddddd).

2. The difference between the three priming conditions will be reflected in the ERP signals. The begin prime followed by fillers will be associated with an earlier component, compared to the end prime preceded by fillers and the unrelated prime.

3. The primes will make no difference on performance in the nonword condition.

Deception

Participants in this study were not informed beforehand about the presence of any type of prime. This was to prevent any conscious processing and thus possible interference of the prime words.

More information?

In case you would like to know more about the research results, you may write your e-mail address on the consent form. As soon as the outcome of the study is known, you will receive an e-mail in which you will find a summary of the study.

In case you like to read more about the topic of the study, you can consult the following literature:

de Vries, P. H. (2016). Neural binding in letter- and word-recognition. In K. E. Twomey, A. Smith, G. Westermann & P. Monaghan (Eds.), *Neurocomputational models of cognitive development and processing: Proceedings of the 14th neural computation and psychology workshop* (pp. 17-33). New Jersey: World Scientific. (Available on request to the author: p.h.de.vries@rug.nl)