Distinguishing a phonological encoding disorder from Apraxia of Speech in individuals with aphasia by using EEG

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Distinguishing a phonological encoding disorder from Apraxia of Speech in individuals with aphasia by using EEG

PhD thesis

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This thesis will be defended in public on

Tuesday 26 January 2021 at 11.00 hours

by

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born on 30 April 1989
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Voor Peter

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List of abbreviations

AAT	Aachen Aphasia Test
ANOVA	analysis of variance
AoA	Age of Acquisition
AoS	Apraxia of Speech
ATP	auditory language comprehension program (in Dutch: Auditief Taalbegripsprogramma)
BA	Brodmann Area
CAT-NL	Dutch version of Comprehensive Aphasia Test
CON	Cingulo-Opercular Network
DIAS	Diagnostic Instrument for Articulation Disorders (in Dutch: Diagnostisch Instrument voor Apraxie van de Spraak)
EEG	electroencephalography
ERP	event-related potential
FPCN	Fronto-Parietal Control Network
MEG	magnetoencephalography
NBDs	non-brain-damaged individuals
PALPA	Psycholinguistic Assessments of Language Processing in Aphasia
PED	phonological encoding disorder
VAT	Verb and Action Test
VEOG	vertical electrooculogram

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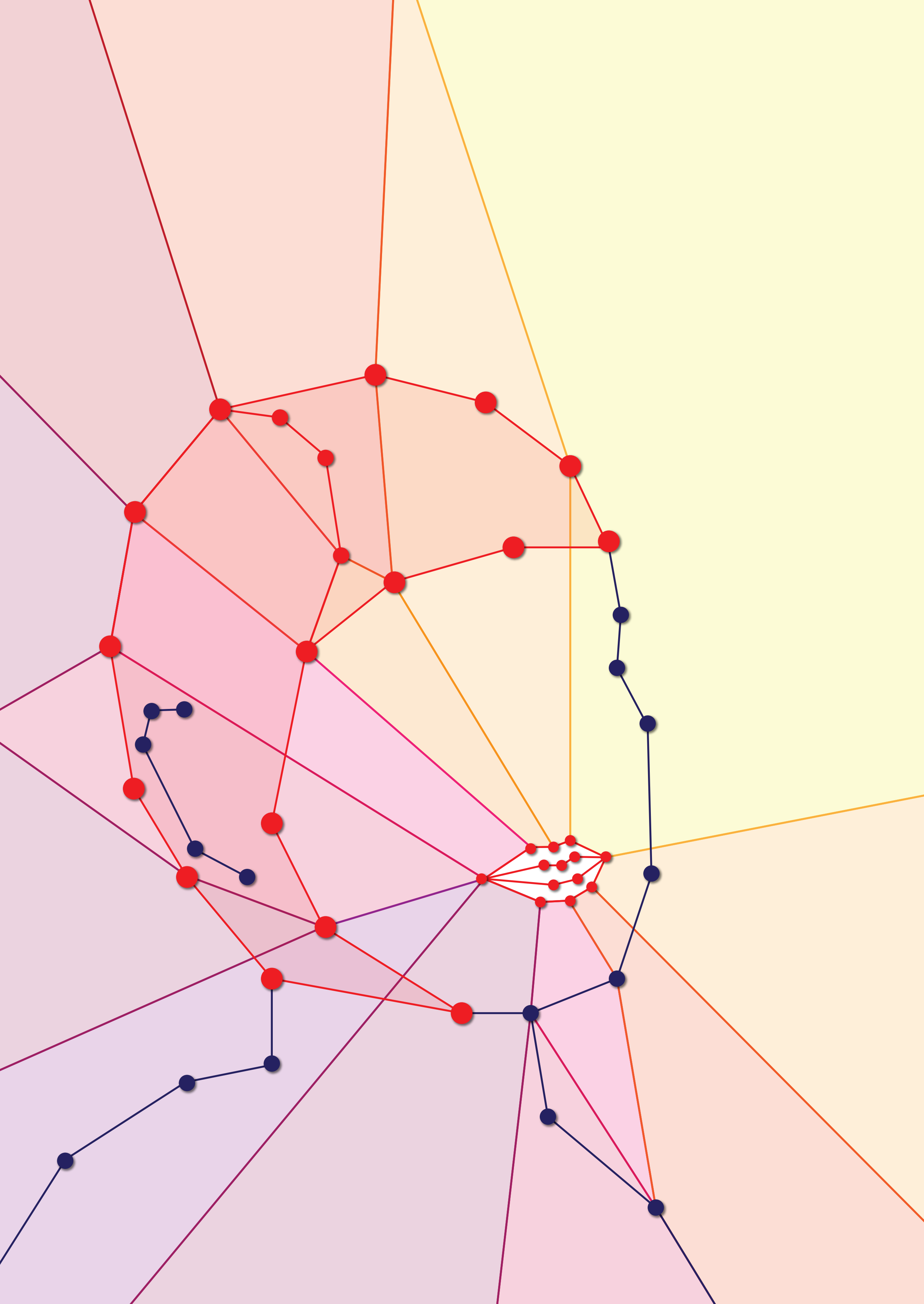


Chapter 1

General introduction

1.1 Introduction

Individuals who suffer from a language disorder after focal brain damage, aphasia, or a speech motor disorder, such as Apraxia of Speech (AoS), experience difficulties in the oral production of words. Errors in their speech production can be related to different problems in the process. If time [taɪm] is produced for tide [taɪd], this error can be related to a problem with retrieving the word or its phonemes. Also, the error can be related to a problem with planning or executing the movements for speech during articulation. These problems correspond to four different stages in the speech production process, which can be independently impaired. Assumptions about the impaired stage can be made by analyzing speech production errors (Den Ouden, 2002; Ellis & Young, 1988). However, just listening to the errors in the speech of individuals with language or speech motor disorders does not reveal the affected stage, because the stages cannot be differentiated on the basis of the acoustic signal alone. Phonemic paraphasias[1], that are substitutions, additions or rearrangements of speech sounds in a word, can be observed in aphasia with a phonological disorder (in the stage during which phonemes are retrieved and ordered), but also in AoS (in the stage during which movements for speech are programmed). It is difficult to identify the impaired stage during which phonemic errors arise (Den Ouden, 2002), particularly because AoS is usually accompanied with aphasia (Nicholas, 2005). As the analysis of speech production errors is not optimal to differentiate a phonological disorder from AoS in individuals with aphasia, another option is to use brain signals for this purpose. Brain signals recorded during speech production tasks using electroencephalography[2] (EEG) can be used to target the speech production stages (Laganaro, 2014). Also, EEG can be used to identify differences in these stages between individuals with aphasia and non-brain-damaged individuals (e.g. Laganaro et al., 2009). It will be studied whether EEG can also be used to differentiate individuals with aphasia and a phonological encoding disorder from individuals with aphasia and AoS.

The first section of the introduction covers the stages that are involved during spoken word and nonword production. The stages are discussed in the context of a speech production model. Moreover, neurophysiological evidence for the stages is provided. In the second section, psycholinguistic and neurolinguistic theories are introduced to make assumptions about stages that are impaired in aphasia and AoS.

[1] In this dissertation, the term 'phonemic paraphasia' is used as a broad term to encompass both phonetic and phonological impairment whilst acknowledging that in the case of phonetic encoding impairments/apraxia of speech the errors may not involve 'phoneme sized' units.

[2] This method is explained in section 1.2.2.

1.2 Oral production of words and nonwords

Models of spoken word production have been developed based on errors produced by individuals who suffer from a language disorder and their performance on various speech production tasks (e.g. Ellis & Young, 1988). Others have been developed based on errors produced by neurologically healthy individuals in combination with linguistic theories (e.g. Dell, 1986; Dell, Juliano, & Govindjee, 1993) or have been based on psycholinguistic experiments with neurologically healthy individuals (e.g. Indefrey & Levelt, 2004; Levelt, Roelofs, & Meyer, 1999). However, not all of these models specify all the processes from conceptualisation to articulation. As Levelt et al.'s (1999) and Indefrey and Levelt's (2004) theory incorporates a stage during which movements for articulation are programmed, which is required to identify AoS, therefore, this is the theory that is the focus of this dissertation. In this thesis, speech production is assessed with picture naming, nonword reading and nonword repetition. The stages that are involved in these tasks are discussed in section 1.2.1.

1.2.1 A model of spoken word production

Picture naming

Stages that are involved in object naming are described in models of spoken word production. In Figure 1.1, the stages are based on the model by Levelt et al. (1999) and Indefrey and Levelt (2004). Next to the model, an example is provided for the word 'rose'.

Conceptual preparation

Object naming starts with seeing the object or the picture. The corresponding lead-in process is visual object recognition (Indefrey & Levelt, 2004). The object is identified during the conceptual preparation stage (Levelt et al., 1999). In Figure 1.1, the target is the word rose. When looking at the picture of a rose, a subject watches a thorny branch with a leaf on the side and many petals at the top of the branch (1). This information is used to access the concept ROSE (2). The concept refers to the meaning of the word.

Lemma retrieval

After the object has been identified and a concept has been built, its lemma can be retrieved. The concept activates lemma nodes, which are abstract word representations that are related to the meaning of the word (Levelt et al., 1999). This is shown in Figure 1.1. The activated lemma nodes for ROSE are the target lemma node ROSE, but its neighboring lemma nodes that are related in meaning, such as TULIP and DAISY, are co-activated (3). The target lemma node receives the highest activation. Thus, the target lemma *rose* is retrieved from the mental lexicon (4). The timing of lemma retrieval starts around 200 ms and ends around 275 ms after the onset time of the presentation of the picture (Indefrey, 2011).

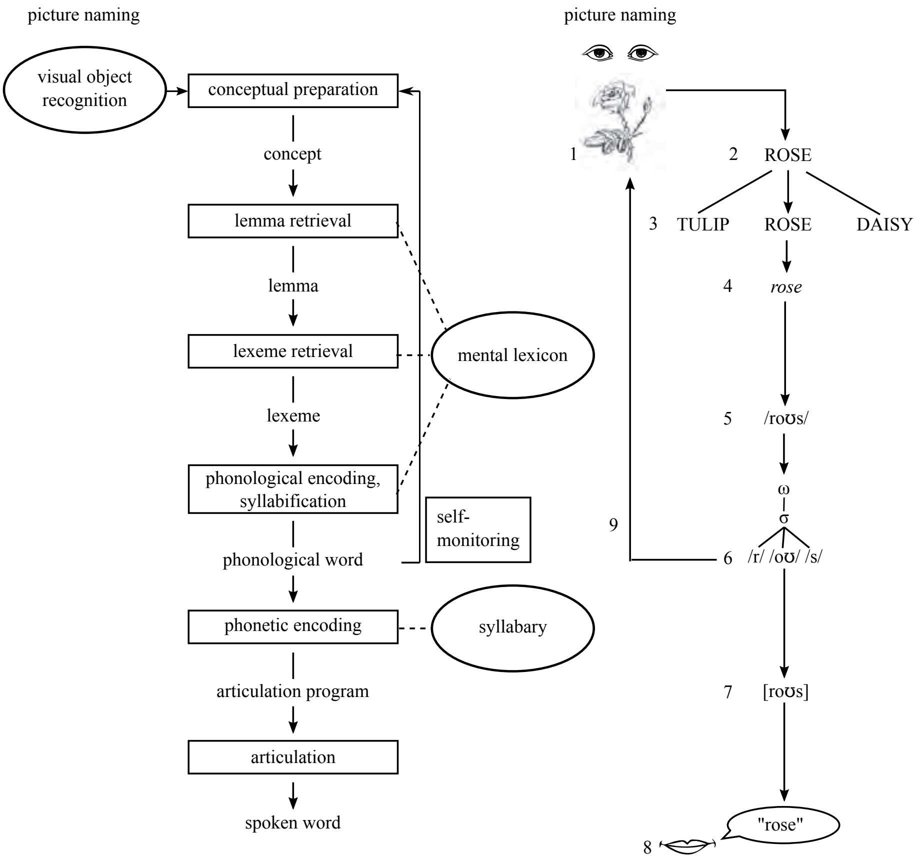


Figure 1.1: The process of picture naming depicted in a model based on Levelt et al. (1999) and Indefrey and Levelt (2004). Stages are represented as boxes. The lead-in process on the left and the storage components on the right are represented as circles. The example for naming the picture of a rose is provided next to the model.

Lexeme retrieval

After lemma retrieval, the underlying phonological word form corresponding to the lemma, the lexeme, is retrieved from the mental lexicon. Lexeme retrieval involves two steps (Levelt et al., 1999). First, the grammatical structure, the morphological code of the lemma, is retrieved from the mental lexicon. In our example, this step results in the morpheme *rose*. If two roses were to be named, the suffix -s for plurality would have been encoded as a second morpheme. Thereafter, the phonological code or the spoken name of the morpheme, the lexeme, is retrieved from the mental lexicon (5). In our example, the lexeme is /roʊs/. The timing of lexeme retrieval starts right after lemma retrieval around 275 ms after the presentation of the picture (Indefrey, 2011).

Phonological encoding

The retrieval and ordering of phonemes corresponding to the slots in the lexeme is referred to as 'phonological encoding'. For the lexeme /roʊs/, the phonemes /r/, /oʊ/ and /s/ are retrieved and placed in the correct order (6). During this stage, the phonological rules, such as assimilation, are applied. Syllabification is the next step, during which the retrieved phonemes are combined into syllables. Here the stress pattern of the phonological word is assigned. The timing of syllabification starts around 355 ms after stimulus presentation (Indefrey, 2011). Its duration depends on the number of phonemes (≈20 ms per phoneme) and the number of syllables (≈50 to 55 ms per syllable).

Phonetic encoding

During phonetic encoding, the phonemes are translated to speech movements (Levelt et al., 1999) (7). Articulation plans are built per syllable. These articulation plans specify the movements of the muscles that are involved in speech, regulate the airflow through vocal tract, and define the position of the velum. The movements are specified on tiers. Imagine these tiers as staves in musical notation. There are staves for opening and closing the vocal cords, for opening and closing the airway to the nose and for mouth movements. Each speech related movement, such as opening the mouth to produce /a/ and closing the mouth to produce /m/, has a unique position on the staves for tongue and lip movements. The notes on the staves define when the movement takes place and the duration. These instructions are called 'gestures'. Notice that at this stage the articulation is programmed, though not yet executed.

The model by Levelt et al. (1999) encompasses a syllabary (Levelt & Wheeldon, 1994). The movements for speech required for frequently produced syllables are stored in the syllabary, whereas movements for less frequently produced syllables have to be computed on demand phoneme-by-phoneme. There have been findings in favor of (e.g. Bürki, Pellet-Cheneval, & Laganaro, 2015; Laganaro & Alario, 2006) and against (Brendel et al., 2011; Riecker, Brendel, Ziegler, Erb, & Ackermann, 2008) the existence of a syllabary. However, it is generally accepted that syllable frequency plays a role in speech production. Phonetic encoding starts as soon as the first syllable is phonologically encoded, which is around 455 ms after stimulus presentation (Indefrey, 2011), thus this stage is incremental.

Articulation

The phonetic code that was programmed at the previous stage is executed during articulation (8). As we exhale, air flows from the lungs through the vocal cords into the oral and nasal cavities. Sound waves are modified by extent to which the airflow is obstructed by the vocal cords, the oral and the nasal cavity. Furthermore, the position and shape of the tongue and lips modify the sound waves. When the articulators (the vocal cords, the oral and nasal cavities, the tongue and the lips) move as programmed, the sound waves are modified in such a manner that the correct string of phonemes is produced. Articulation takes place around 600 ms after stimulus presentation (Indefrey, 2011).

Self-monitoring

Every stage of the speech production process is monitored by the speaker. After phonological encoding, for example, it is verified whether the retrieved phonological word matches the conceptual representation through the 'inner loop' (Indefrey, 2011; Oomen, Postma, & Kolk, 2005), as shown in Figure 1.1 (9).

Nonword reading and repetition

We cannot only produce words that we know, but we can also read and repeat non-existing words, so called 'nonwords'. Nonwords are composed of syllables that follow the phonological rules of the target language. An example of a nonword in Dutch is written as 'kikkels' and sounds like /kɪ'kəls/. The stages involved in reading and repetition of nonwords are shown in Figure 1.2. Nonword reading starts with a written visual input (1a). First, the string of graphemes is analyzed (2a) (Bastiaanse, 2010; Ellis & Young, 1988). The visual analysis system identifies the graphemes of the nonword, for example <k>, <i>, <k>,<k>, <e>, <l> and <s>. The graphemes are converted to phonemes (3a). Nonword repetition starts with an auditory input (1b). The heard string of phonemes is analyzed (2b). The auditory analysis system identifies the phonemes of the heard nonword in the correct order, for example /k/ /ɪ/ /k/ /ə/ /l/ /s/ (3b). Since the nonword is processed as an unknown word, the recognized string of phonemes has no matching lexical entry. Therefore, lexical stages are skipped and a sublexical route is used (Bastiaanse, 2010; Ellis & Young, 1988). From phonological encoding onwards, the stages in nonword reading and repetition are identical to those of picture naming. During phonological encoding the string of phonemes is retrieved and ordered (4). Articulation plans are built during phonetic encoding (5) and executed during articulation (6). As with the production of words, monitoring takes place for every speech production stage. The 'inner loop' is used to compare the phonological word to the written input in the reading task (7a) or to the heard input in the repetition task (7b).

Linguistic features that have an effect on speech production stages

The speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding are reported on in this dissertation. Various linguistic features have an effect on these stages. These features are discussed in this section in the order of their appearance in the word production model.

Lemmas are stored on the basis of semantics, that is, lemmas that are closely related in meaning (animals; furniture) are stored together. This means that in the activation and co-activation process, the target lemma is activated and semantically related lemmas are co-activated. For example, when the picture of a rose has to be named, then ROSE is the target lemma and the lemmas TULIP and DAISY are co-activated. If TULIP is the next lemma that needs to be retrieved, there is increased competition between the lemmas ROSE and TULIP. Therefore, the selection of TULIP requires more time. Thus, lemma retrieval is slower in a picture naming task when the number of previously named pictures of a particular semantic category increases. This effect is the 'cumulative semantic interference effect' (Howard, Nickels, Coltheart, & Cole-Virtue, 2006). Also, low imageability lemmas, such as 'HOPE', require more time for lemma retrieval than highly imageable lemmas (Bastiaanse, Wieling, & Wolthuis, 2016). More errors are observed in the production of low imageability lemmas as compared to high imageability lemmas (Nickels & Howard, 1994). Furthermore, increased time is required for the retrieval of low frequency lemmas as compared to high frequency lemmas (Bastiaanse et al., 2016).

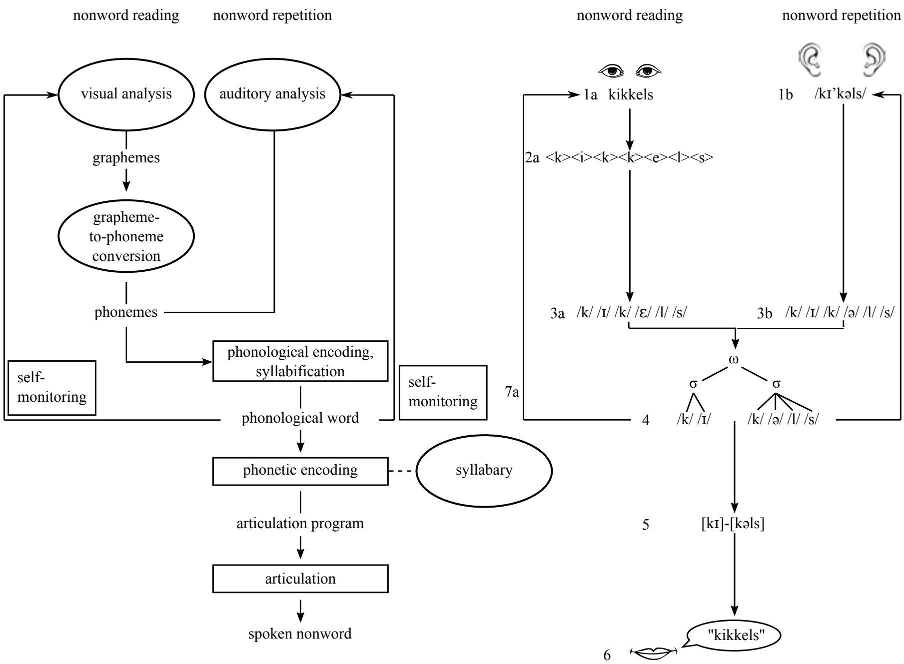


Figure 1.2: The process of nonword reading and repetition depicted in a model based on Ellis and Young (1988) and Indefrey and Levelt (2004). Stages are represented as boxes. The lead-in processes on top with the stage 'grapheme-to-phoneme conversion' and the storage component on the right are represented as circles. The example for producing the nonword 'kikkels' is provided next to the model.

At the level of lexeme retrieval there is evidence for an age of acquisition (AoA) effect (Bastiaanse et al., 2016; Chalard & Bonin, 2006; Kittredge, Dell, Verkuilen, & Schwartz, 2008; Laganaro & Perret, 2011; Laganaro, Valente, & Perret, 2012; Morrison & Ellis, 1995;

Morrison, Ellis, & Quinlan, 1992; Nickels & Howard, 1995). Lexemes of words that are acquired at an earlier age in life, such as 'bed', are retrieved faster than lexemes of words with a later AoA, such as 'anchor'. Also, lexeme frequency has an effect on lexeme retrieval (Bastiaanse et al., 2016; Jescheniak, & Levelt, 1994; Kittredge et al., 2008; Nickels & Howard, 1995). Increased lexeme retrieval time is found for low frequency lexemes as compared to high frequency lexemes. However, since word frequency and AoA are closely correlated, we only use AoA in the current study.

Word length in phonemes, morphemes, and syllables has an effect on phonological encoding (Damian, Bowers, Stadthagen-Gonzalez, & Spalek, 2010; Ellis & Young, 1988; Meyer, Roelofs, & Levelt, 2003). Phonological encoding time increases as word length advances. In longer words, more phonemes need to be phonologically encoded. Words that consist of more syllables require additional phonetic encoding time as well, because more syllables need to be phonetically encoded. Also, phonetic encoding time increases for low frequency syllables as compared to high frequency syllables. This observation has often been related to the existence of the syllabary (e.g. Bürki et al., 2015; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994), from which the articulation plans of high frequency syllables can be retrieved.

In the current study, lemma and lexeme retrieval are studied in picture naming paradigms. In the lemma retrieval task, items are manipulated for semantic relatedness. Items are manipulated for AoA in the lexeme retrieval task. A nonword reading paradigm and a nonword repetition paradigm are used to track phonological and phonetic encoding. Items manipulated for nonword length in phonemes are used to identify phonological encoding. Although nonword length in phonemes may also affect phonetic encoding, this is not a problem, because the onset of this effect on phonological encoding precedes its onset on phonetic encoding (Indefrey, 2011). To identify phonetic encoding, nonwords that are manipulated for syllable frequency are used. Items have been carefully controlled for the previously mentioned linguistic features that can have an effect on the studied speech production stages. An overview of the stages and how they are studied is provided in Figure 1.3.

1.2.2 Neurophysiolozgical measures of spoken word and nonword production stages

EEG

In this thesis, electroencephalograms will be registered to track down speech production stages in the brain. Electroencephalography (EEG) measures small changes in electrical brain activity using electrodes on the scalp. Figure 1.4 shows how brain activity works. Electrical brain activity originates from networks in the brain (Luck, 2005). The building blocks of these networks are neurons (1). The dendrites (2) of a neuron receive signals from other neurons. A neuron fires when a signal passes the threshold potential in the axon hillock (3). The signal is conducted through the axons (4) into the presynaptic cell (5). The presynaptic cell releases neurotransmitter into the synaptic cleft (6), which is received by the postsynaptic cell (7). The postsynaptic cell acts like a dipole (8). The neurotransmitter binds to the membrane (9) of the postsynaptic cell. This causes some channels to open, and, thus, Na^+ ions can flow into the postsynaptic cell, which makes the current drop on one end of the dipole, while at the other end of the dipole an active source of current is produced. This results in a postsynaptic potential, which lasts for tens to hundreds of milliseconds. EEG is a method to register the current from the dipoles using electrodes that are placed at the scalp and to visualize the current in an electroencephalogram. However, the current from the dipoles can only be measured at the scalp when large clusters of pyramidal neurons, which are positioned in parallel, simultaneously show the same type of postsynaptic potential (Pascual-Marqui, Sekihara, Brandeis, & Michel, 2009).

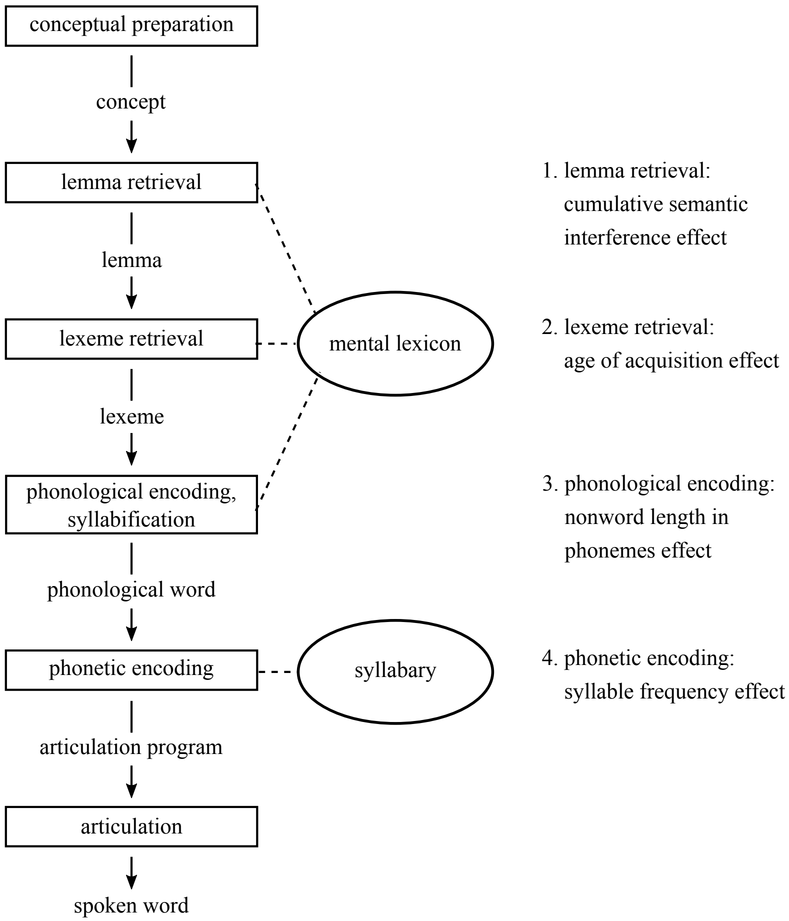


Figure 1.3: Effects used to identify the stages in speech production discussed above.

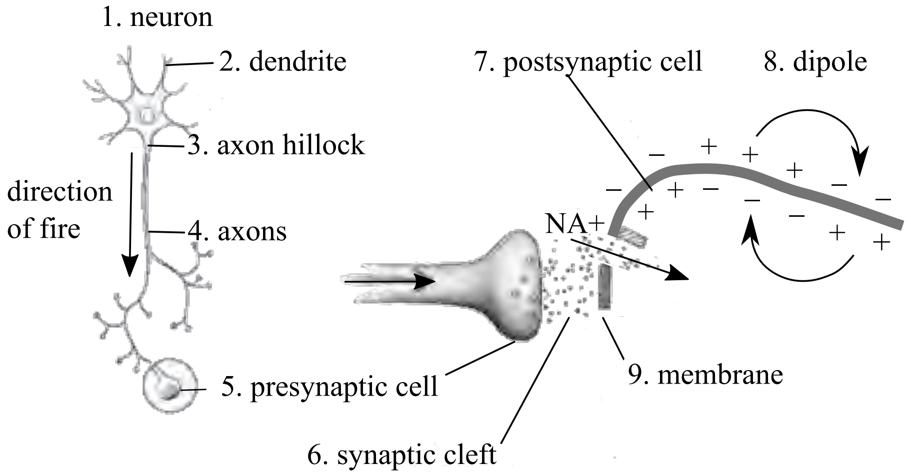


Figure 1.4: Brain potentials. A neuron is depicted on the left side. The right side is an enlargement of the presynaptic cell. It shows how NA+ ions flow into the postsynaptic cell, which creates a dipole. The figure is adapted from Noback, Strominger, Demarest, & Ruggiero (2005).

In our setup, the scalp electrodes are evenly distributed over the scalp. The location of the electrodes is based on the 10-20 system, which has been designed for a cap with 32 electrodes (Jasper, 1958). In our setup 64 and 128 electrodes caps are used, which are depicted in Figure 1.5. Electrodes are placed in vertical rows from the forehead to the back of the scalp and in horizontal rows from ear to ear. With the 64 electrodes cap, the 10-10 system is used. This means, that the distance between the horizontal rows is 10% of the distance between the most frontal and the most posterior electrode. The distance between the vertical rows is 10% of the distance from ear to ear. With the 128 electrodes cap, the 10-5 system is used. This means that the distance between the horizontal rows is 5% of the distance between the most frontal and the most posterior electrode. The distance between the vertical rows is 5% of the distance from ear to ear. In both caps, the most frontal electrode is placed at 10% above the nasion, the bridge between the nose and the stern. The most posterior electrode is placed at 10% above the inion, the back of the scalp, in the 64 electrodes cap. In the 128 electrodes cap, the most posterior electrode covers the inion.

The brain activity is amplified so it can be visualized on a computer screen as variations in amplitude of electric potential over time. The pure brain signal without noise should have an amplitude ranging from -100 µV to +100 µV and a maximum frequency of 40 Hz (Coles & Rugg, 1996). The continuous EEG signal cannot be used to study a speech production stage. The signal is studied as a response to a stimulus or an event. The participant in a speech production experiment encounters many stimuli of the same type. These responses are averaged to find the electrophysiological response to an event, the event-related potential (ERP). It is common practice to analyze a selection of electrodes in a particular time window to find an ERP. In the current study, all scalp electrodes have been analyzed in a time window from stimulus onset until 100 ms before response onset. Therefore, stimulus-locked analyses, in which the time window after the stimulus onset is analyzed, and response-locked analyses, in which the backwards time window before the response onset is analyzed, were carried out.

Previous studies have used EEG (or MEG[3]) to investigate linguistic features that can be applied to target the time course of particular speech production stages. These studies are discussed in order of appearance of the stages in the model of spoken word production.

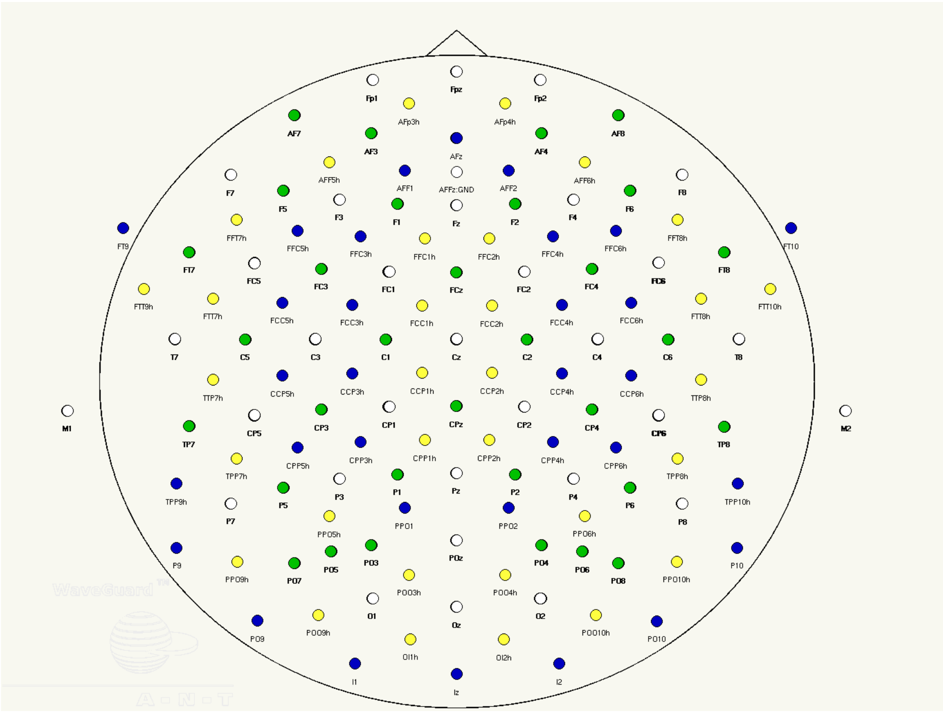


Figure 1.5: The layout of a 64 electrodes cap is depicted as white and green circles that are placed according to the 10-10 system. The layout of a cap with 128 electrodes that are placed according to the 10-5 system is depicted with the white, green, blue and yellow circles. The figure is retrieved from http://www.ant-neuro.com/sites/default/files/images/waveguard_layout_128ch.png.

[3] MEG (magnetoencephalography) is a method to measure brain activity originating from dipoles in the brain.

Neurophysiological evidence for the time course of lemma retrieval

According to Indefrey (2011), lemma retrieval starts around 200 ms and ends around 275 ms after stimulus onset. The cumulative semantic interference effect, which is used to target lemma retrieval in the current study, has been reported on in an EEG study (Costa, Strijkers, Martin and Thierry, 2009) and in a MEG study (Maess, Friederici, Damian, Meyer, & Levelt, 2002). The effect was elicited with the successive presentation of pictures of five semantically related words (e.g. train, bike, car, airplane and bus; Maess et al., 2002). Naming latencies increased with the number of consecutive items of the same category that had to be named. A difference between the first and the fifth consecutive item of the same category was identified in the EEG data from 150 to 225 ms after stimulus onset (Maess et al., 2002) and from 200 to 380 ms after stimulus onset (Costa et al., 2009). The later time window identified in the study by Costa et al. (2009) can be explained by variation in lemma frequency. In the study by Maess et al. (2002), only words with a high lemma frequency were used, whereas in the study by Costa et al. (2009) also words with a low lemma frequency have been included. Retrieval of low frequency lemmas is more effortful, which has caused longer response times in the study by Costa et al. (2009) as compared to the study by Maess et al. (2002) and is likely to have influenced the time window of the effect as well.

The picture-word interference paradigm has previously been tested in EEG studies (Dell'Acqua et al., 2010; Hirschfeld, Jansma, Bölte, & Zwitserlood, 2008) and can be used to track the time course of lemma retrieval. Dell'Acqua et al. (2010) found that simultaneously presented semantically related words slowed down picture naming compared to simultaneously presented semantically unrelated words. A difference between these conditions was found in the EEG data at latencies of 106 ms and 320 ms after stimulus presentation. In the study by Hirschfeld et al. (2008), words were presented 150 ms before picture presentation. Categorically related words (e.g. the word 'dog' and a picture of a 'cat') slowed picture naming, whereas associated feature words (e.g. the word 'fur' and a picture of a 'cat') speeded picture naming compared to unrelated words. The EEG signal differed between the conditions from 120 to 220 ms after picture presentation. Categorically related words caused a negativity, whereas associated feature words caused a positivity compared to unrelated words in this time domain. In a blocked cyclic naming paradigm with picture-word interference, distractor words were presented auditorily 150 ms before the onset of the picture (Aristei, Melinger, & Abdel Rahman, 2011). This study encompassed picture naming in homogeneous blocks of one semantic category and heterogeneous blocks of mixed semantic categories. The EEG signal of the related words preceding the picture showed a negativity compared to the unrelated target words only in the homogeneous blocks. The time window was later than in Hirschfeld et al. (2008): from 200 to 550 ms after the picture presentation. In the heterogeneous blocks, which were more comparable to the stimuli by Hirschfeld et al., no effects were found.

The effect of lemma frequency has also been tested with EEG and this variable can be used to track the time course of lemma retrieval (Strijkers, Costa and Thierry, 2010). Strijkers et al. found that picture naming latencies increased as lemma frequency decreased. Their EEG data showed a positivity for words with a low lemma frequency compared to words with a high lemma frequency starting from 180 ms after stimulus presentation. The effect of imageability in picture naming has also been examined with EEG and can be used to track lemma retrieval. The comparison of highly imageable object nouns, and low imageability action nouns, revealed a positivity in the EEG data from 250 to 380 ms after stimulus presentation (Fargier and Laganaro, 2015). In sum, lemma retrieval has been identified using EEG and MEG between 106 ms (Dell'Acqua et al., 2010) and 550 ms (Hirschfeld et al., 2008) after stimulus presentation (see Figure 1.6).

Neurophysiological evidence for lexeme retrieval

Indefrey (2011) proposed that lexeme retrieval starts around 275 ms after stimulus presentation. In previous EEG studies, the AoA effect, which is used to target lexeme retrieval in the current study, has been identified by comparing the production of words with an early AoA (1,7 years) to later acquired words (2,7 years) in a picture naming task (Laganaro & Perret, 2011; Laganaro et al., 2012; Valente, Bürki, & Laganaro, 2014). Early acquired words had a shorter naming latency than later acquired words. Using EEG, an AoA-effect has been identified between 120 and 350 ms after stimulus presentation (Laganaro & Perret, 2011). Also, the effect has been observed from 380 ms after stimulus presentation up to 200 ms before response onset (Laganaro et al., 2012) as well as from 380 ms after stimulus presentation up to 100 ms before response onset (Valente et al., 2014). These results are quite different from the results by Laganaro and Perret (2011) (and the timing of Indefrey, 2011). These differences in timing of the effect may be influenced by variation between participants. For example, an earlier effect was reported in fast speakers as compared to slow speakers (Laganaro et al., 2012).

An effect of lexeme frequency, which also influences lexeme retrieval, has been identified in picture naming tasks using MEG (Levelt, Praamstra, Meyer, Helenius, & Salmelin, 1998) and EEG (Laganaro et al., 2009). Naming latencies of low frequency lexemes were longer than those of high frequency lexemes. The time windows of the lexeme frequency effect were from 150 to 400 ms after picture presentation (Levelt et al., 1998) and between 270 and 464 ms after picture presentation (Laganaro et al., 2009).

Moreover, lexeme retrieval has been studied using gender and phoneme monitoring tasks in picture naming (Camen, Morand, & Laganaro, 2009). Participants (native speakers of French) were asked to indicate whether the grammatical gender of the depicted word was masculine or feminine, and in another task whether the first or the second syllable of the word presented on the picture started with a particular phoneme. Comparing correct and incorrect conditions, effects of both gender and phoneme monitoring were found from 270 to 290 ms after stimulus presentation. In sum, lexeme retrieval has been identified between 120 ms after stimulus presentation (Laganaro & Perret, 2011) and up to 100 ms before response onset (Valente et al., 2014) (see Figure 1.6).

Neurophysiological evidence for phonological encoding

Phonological encoding, or syllabification, has been suggested to start around 355 ms after stimulus onset (Indefrey, 2011), and have a duration of approximately 20 ms per phoneme and 50 to 55 ms per syllable. The effect of nonword length in phonemes, which is used to track phonological encoding in the current study, has not been reported on in previous EEG studies. However, the effect of word length has been studied with picture naming tasks using EEG (Hendrix, Bolger, & Baayen, 2017; Valente et al., 2014). In these studies, no effect of word length was identified. In picture naming tasks, the input to the phonological encoding stage is a lexeme, whereas, in nonword production tasks, the input to the phonological encoding stage is an unfamiliar string of phonemes. The phonological encoding of the this unfamiliar string of phonemes may require more processing resources and, consequently, the requirement to encode additional phonemes may have a larger impact on the processing load and therefore, this may show an effect in the EEG data.

During picture naming, interference from a lexeme that is phonologically related to the picture has an impact on phonological encoding as well. Using a picture-word interference paradigm with phonologically related words, Dell'Acqua et al. (2010) found increased response times for pictures that were named with simultaneous presentation of a phonologically related word as compared to a phonologically unrelated word. In the EEG data, a difference between these conditions was identified around 321 ms after stimulus presentation (see Figure 1.6).

Neurophysiological evidence for phonetic encoding

After the first syllable has been phonologically encoded, around 455 ms after stimulus onset, phonetic encoding starts (Indefrey, 2011). Two previous EEG studies have reported on the syllable frequency effect, which is used to target phonetic encoding in the current study (Bürki et al., 2015; Laganaro, 2011). Bürki et al. (2015) provided converging evidence for Levelt and Wheeldon's (1994) claim that the articulation plans of novel syllables have to be built, whereas the articulation plans of high frequent syllables can be retrieved as a whole from the syllabary. In the EEG data, nonwords with novel syllables showed a positivity compared to nonwords with high frequency syllables from 170 to 100 ms before articulation onset. In a nonword reading task without additional manipulations, Laganaro (2011) identified a syllable frequency effect starting around 300 ms before response onset (see Figure 1.6). A syllable frequency effect has not yet been studied in nonword repetition tasks. In sum, EEG effects related to phonetic encoding have been found between 300 (Laganaro, 2011) and 100 ms (Bürki et al., 2015) before articulation onset.

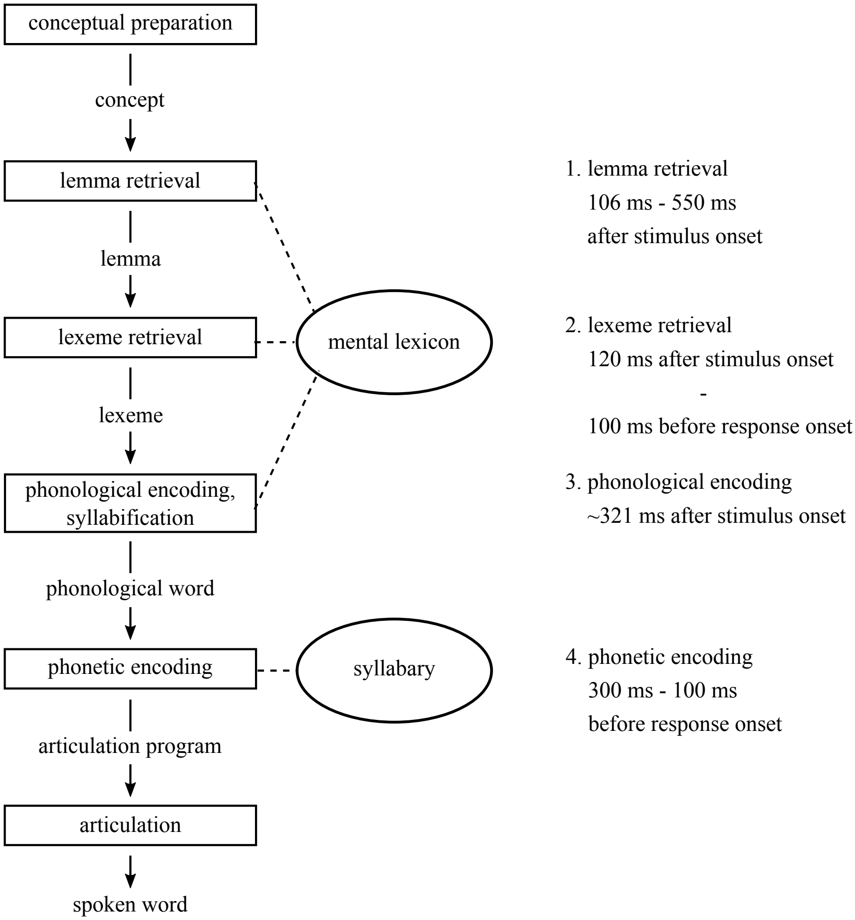


Figure 1.6: The time windows of lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding based on the literature discussed in this section.

1.3 Symptoms in speech production

Impairments in speech production have been observed in aphasia and AoS. Aphasia is an acquired language disorder, caused by focal brain injury that arises after language acquisition has been completed (Bastiaanse, 2010). AoS is an impairment in programming the positioning of speech articulators and the sequencing of the articulation (Darley, Aronson, & Brown, 1975; Jonkers, Feiken, & Stuive, 2017; Ziegler, 2008). In aphasia, the impairment is purely linguistic in nature. Errors may arise during lemma retrieval, lexeme retrieval and/or phonological encoding (Nickels, 1997). In AoS, the errors arise during phonetic encoding (Darley et al., 1975; Jonkers et al., 2017; Miller & Wambaugh, 2017; Varley & Whiteside, 2001; Ziegler, 2008). Pure AoS is rare, as it is usually accompanied with aphasia (Nicholas, 2005). The speech production stages in which impairments may be observed in aphasia and AoS are shown in Figure 1.7. Impairments of lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding will be described in this section.

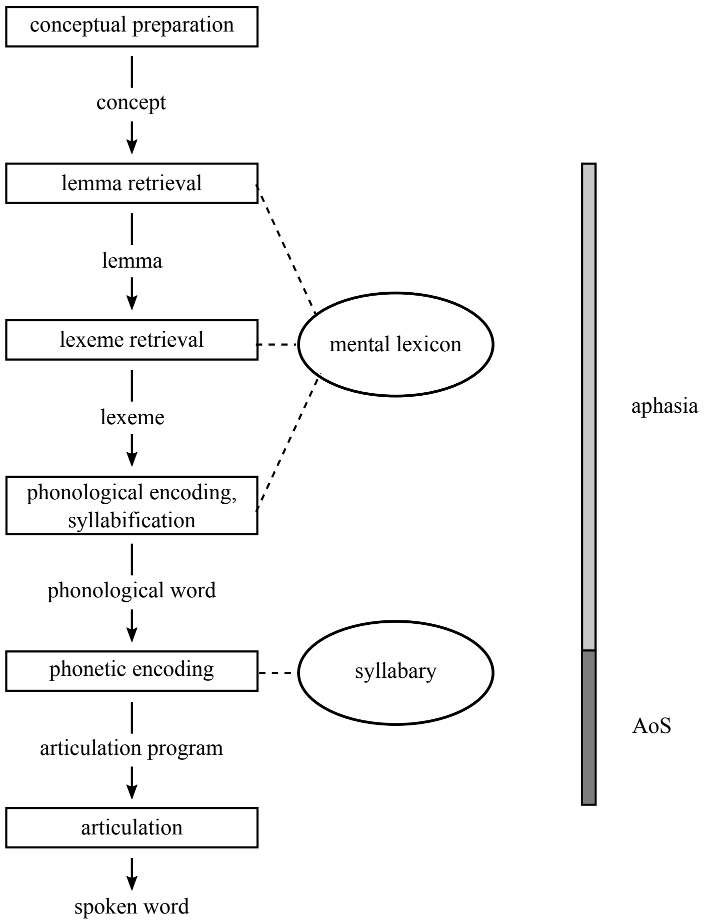


Figure 1.7: Impairments in speech production stages that can be observed in aphasia and AoS depicted in the model discussed above.

1.3.1 Underlying impairments

Lemma retrieval

A disorder in lemma retrieval may cause semantic paraphasias. Semantic paraphasias may occur when the target lemma is not sufficiently activated and, therefore, a semantically related lemma that was co-activated was retrieved, for example, the error *tulip* for *rose* (Howard &

Orchard-Lisle, 1984). As only lemmas of existing words are stored in the mental lexicon, the error will be an existing word. Words with a lower imageablility are more vulnerable than words with a higher imageability (Nickels & Howard, 1994). This is in line with the results of a study by Bastiaanse et al. (2016), who found that more concrete words are easier to retrieve for individuals with aphasia.

Lexeme retrieval

If the incorrect lexeme is selected from the lexicon, the error will be an existing word, because only words are stored in the lexicon. Lexemes are stored based on their phonological structure. Thus, if a neighboring lexeme of the target lexeme is selected, this lexeme is likely to at least partially overlap in phonological structure with the target word (Bastiaanse, 2010; but see Ellis & Young, 1988 for other error types that may arise at this level). Frequency and AoA of the lexemes play an important role in lexical retrieval in individuals with aphasia (Bastiaanse et al., 2016; Kittredge et al., 2008; Nickels & Howard, 1995). They experience more difficulties in retrieving words with a lower lexeme frequency and words that are acquired at a later age as compared to retrieving words with a higher lexeme frequency and words that are acquired at an earlier age.

Phonological and phonetic encoding

Phonemic paraphasias (speech sound errors, i.e., substitutions, deletions, additions or transpositions of speech sounds), may occur due to a disorder in phonological and/or phonetic encoding. In case of an impairment in phonological encoding, these errors arise when the phonological word form is not fully retrieved, when a wrong phoneme is retrieved, when the phonemes are ordered incorrectly or a combination thereof (Laganaro & Zimmermann, 2010; Laganaro, 2012). This may result in an existing or a non-existing word. The produced word is usually phonologically related to the target word, unless the disorder is severe. According to Ellis and Young (1988), individuals with aphasia who have a disorder in phonological encoding have more problems with producing longer words than with producing shorter words.

In the case of an impairment in phonetic encoding, phonemic paraphasias are caused by a problem in the translation of syllables into articulation plans, and this is the source of impairment in AoS (Miller & Wambaugh, 2017). More problems are observed in words with increased articulatory complexity (Canter, Trost, & Burns, 1985; Johns & Darley, 1970; Peach & Tonkovich, 2004), such as words with consonant clusters. Also, more errors are produced in words with lower frequency syllables as compared to words with higher frequency syllables (Aichert & Ziegler, 2004), although Varley and Whiteside (2001) did not find such a syllable frequency effect. An effect of syllable frequency has also been observed in some individuals with a phonological disorder (Laganaro, 2005; Laganaro, 2008). In their speech production, low frequency syllables were replaced with higher frequency syllables. This can be explained by the interaction between phonological and phonetic encoding. During phonological encoding, lacking phonological information may cause selection of high frequency syllables that are available at the level of phonetic encoding. Another possibility is that the feedback from the phonetic encoding stage may facilitate the production of high frequency syllables. Thus, in case of impairments in both phonological and phonetic encoding, there is an interaction between these stages and, therefore, it is difficult to distinguish these impairments in people with aphasia and AoS (Laganaro, 2012).

1.3.2 Differentiating AoS from aphasia with a phonological encoding disorder

Characteristics in the speech of an individual with aphasia or AoS can be used to make inferences about the impaired stage in the model of spoken word production. Den Ouden (2002) used a protocol with a naming task, a repetition task and a phoneme identification task to pinpoint the impaired stage in individuals with aphasia and in individuals with a combination of AoS and aphasia. While lexical and phonological impairments could be differentiated using the protocol, differentiating a phonological disorder from a phonetic disorder in linguistic terms was difficult (but see Bastiaanse, Gilbers, & Van der Linde, 1994; Gilbers, Bastiaanse, & Van der Linde, 1997). The impaired stage identified using the protocol did not correspond to the original diagnosis for one individual with conduction aphasia and for the individuals with a combination of AoS and aphasia. AoS is usually accompanied by nonfluent aphasia, but may also occur with fluent aphasia (Nicholas, 2005). The co-morbidity of AoS and aphasia is a major problem for their differentiation. Also, characteristics in speech production that can be present in both AoS and in aphasia with a phonological disorder are problematic for differentiating both disorders. This issue will be addressed in the next paragraph. Thereafter, it will be discussed whether the localization of the lesion in the brains of individuals with aphasia and AoS can be used to distinguish the disorders.

Characteristic-based differentiation

The Diagnostic Instrument for Apraxia of Speech (DIAS) (Feiken & Jonkers, 2012) is based on characteristics in the speech of individuals with AoS. This instrument is commonly used for the diagnosis of AoS in Dutch. According to Jonkers et al. (2017), the presence of three out of eight criteria is sufficient to diagnose the presence of AoS. Some of these characteristics are unique to AoS, whereas others may also be present in aphasia with a phonological disorder, as shown in Table 1.1. Characteristics of AoS are also seen in speakers with aphasia, but Jonkers et al. (2017) demonstrated that 90% of the speakers with aphasia and without AoS presented with only one or two of these characteristics.

Table 1.1: The presence of characteristics that are associated with AoS in aphasia with a phonological disorder.

Characteristic of AoS	Possible presence in aphasia with a phonological disorder
1) Same phoneme is produced accurately for one repetition and inaccurately for another repetition.	Yes, but variability of error type is larger in AoS (Bislick, McNeil, Spencer, Yorkston, & Kendall, 2017; Haley, Jacks, & Cunningham, 2013), .
2) More errors in the production of consonants than vowels at the phoneme level.	Yes.
3) Discrepancy between rapid production of sequential and alternating constructions in diadochokinesis.	Yes, but the discrepancy is smaller than in AoS (Deger & Ziegler, 2002; Ogar, Willock, Baldo, Wilkins, Ludy, & Dronkers, 2006; Wertz et al., 1984; Ziegler, 2002).
4) Visible and audible groping.	Yes, but only three cases were reported (McNeil, Odell, Miller, & Hunter. 1995; Paghera, Mariën, & Vignolo, 2003).
5) Problems with initiating speech.	No.
6) Segmentation of syllables.	No.
7) Segmentation of consonant clusters.	No.
8) More errors in words with increased articulatory complexity.	Yes.

1

1) Same phoneme is produced accurately for one repetition and inaccurately for another repetition.

The same phoneme can be produced accurately for one repetition and inaccurately for another repetition in AoS (Darley, Aronson, & Brown, 1975; La Pointe & Johns, 1975; Romani & Galluzi, 2005; Varley & Whiteside, 2001; Wertz, LaPointe, & Rosenbek, 1984). It is hard to predict whether individuals with AoS will produce an error, but if they produce an error, its pattern is often predictable based on the environment. In several studies, it has been found that individuals with aphasia as well as individuals with AoS often make errors on the same phoneme across word repetitions (e.g. Bislick et al., 2017; McNeil et al., 1995). There is discussion about whether the type of error produced on the same phoneme has a high (Bislick et al., 2017; Haley et al., 2013) or a low variability (McNeil et al., 1995) in individuals with AoS as compared to individuals with aphasia.

2) More errors in the production of consonants than vowels at the phoneme level.

The fact that consonants are produced incorrectly more often than vowels is not unique to AoS (Miller & Wambaugh, 2017). Caramazza et al. (2000) described two cases of aphasia with a phonological disorder. One case (AS) produced more errors on vowels than consonants, whereas the second case (IFA) produced more errors on consonants than vowels, which is often observed in conduction aphasia (Caramazza, Chialant, Capasso, & Miceli, 2000) and in AoS.

3) Discrepancy between rapid production of sequential and alternating constructions in diadochokinesis.

The discrepancy between the rapid production of repeated sequential (pa-pa-pa) and alternating (pa-ta-ka) syllable strings in a diadochokinesis task is larger in AoS than in aphasia (Deger & Ziegler, 2002; Ogar et al., 2006; Wertz et al., 1984; Ziegler, 2002). Alternating diadochokinesis is more impaired than sequential diadochokinesis in aphasia and in AoS (Deger & Ziegler, 2002; Ogar et al., 2006; Wertz et al., 1984; Ziegler, 2002).

4) Visible and audible groping.

Groping is observed when the lips and tongue are searching for the correct position and movement in order to articulate a phoneme (Darley et al., 1975; Fromm, Abbs, McNeil, & Rosenbek, 1982; Johns & Darley, 1970; Wertz et al., 1984), a typical characteristic of AoS. However, there are few exceptions described in the literature. A right-handed individual with aphasia with a phonological disorder exhibited groping after a right-hemisphere lesion, even though she was not suffering from AoS (Paghera et al., 2003). McNeil et al. (1995) discussed two cases of individuals with aphasia with a phonological disorder who exhibited groping. The criteria used by McNeil et al. (1995) to differentiate AoS from aphasia with a phonological disorder may not have been identical to the criteria used for the diagnosis of AoS in the DIAS (Feiken & Jonkers, 2012).

5) Problems with initiating speech.

Problems with initiating speech are a characteristic of AoS (Kent & Rosenbek, 1983; Peach & Tonkovich, 2004; Towne & Crary, 1988) as well as a characteristic of nonfluent aphasia, such as Broca's aphasia (Stewart & Riedel, 2015). Speech initiation difficulties are not a characteristic of fluent aphasia, such as conduction aphasia, where the disorder is located at the level of phonological encoding (Den Ouden & Bastiaanse, 2005; Kohn, 1988).

6) Segmentation of syllables and 7) segmentation of consonant clusters.

The segmentation of syllables and consonant clusters into phonemes by inserting pauses is a typical characteristic of AoS (Kent & Rosenbek, 1983).

8) More errors in words with increased articulatory complexity.

The production of more errors in words with consonant clusters (Johns & Darley, 1970; Peach & Tonkovich, 2004) is not unique to AoS. Simplification of consonant clusters in speech production has been observed in individuals with aphasia (Kohn, 1988). However, it has been suggested that, depending on the severity of the disorder, the difference between the number of errors in consonant clusters and the number of errors in consonant singletons is smaller in a phonological disorder compared to AoS (Canter et al., 1985).

Thus, six out of eight characteristics that can be present in AoS can also, even though to a lesser extent, be observed in individuals with aphasia suffering from a phonological disorder.

Lesion-based differentiation

Lesions caused by a stroke are often large and, therefore, have an impact on many cognitive functions (Bartels, Duffy, & Beland, 2015). In right-handed individuals, lesions causing aphasia as well as AoS are generally found in the left perisylvian cortex (Moser, Basilakos, Fillmore, & Fridriksson, 2016). Aphasia can result from damage to or around the inferior frontal gyrus, which is referred to as Broca's area. Broca's area is composed of the pars opercularis, Brodmann Area (BA) 44, and the pars triangularis, BA 45. AoS can arise from a lesion in Broca's area as well (Bonilha, Moser, Rorden, Baylis, & Fridriksson, 2006; Hillis et al., 2004; Richardson, Fillmore, Rorden, LaPointe, & Fridriksson, 2012; Square-Storer, Roy, & Martin, 1997; Trupe et al., 2013). Furthermore, aphasia can result from damage to or around the superior temporal gyrus, BA 22, which is known as Wernicke's area. Aphasia with a phonological disorder can result from damage in the connection between Broca's and Wernicke's area, the arcuate fasciculus (Catani & Mesulam, 2008; Geschwind, 1965). Damage to the posterior part of the Sylvian fissure has been associated with aphasia with a phonological disorder as well (Buchsbaum, et al., 2011).

Damage to the insula, BA13-16, a lobe inside the Sylvian fissure, has been associated with AoS (Dronkers, 1996; Moser et al., 2016; Richardson et al, 2012; Square-Storer et al., 1997). The insula is possibly involved in composing motor programs (Moser et al., 2009). A lesion to the insula may cause mild AoS, whereas a lesion to both the insula and Broca's area may cause more severe AoS (Ogar et al., 2006). Regions that are associated with AoS deeper in the brain are the lentiform nucleus (Square-Storer et al., 1997) and the basal ganglia (Peach & Tonkovich, 2003). Furthermore, AoS can be caused by damage to areas required for motor control over the mouth and throat in the motor cortex in the left hemisphere (Alexander, Benson, & Stuss, 1989; Moser et al., 2016). Relevant areas are the sensorimotor cortex, BA 1-3, (Basilakos, Rorden, Bonilha, Moser, & Fridriksson, 2015; Riecker et al., 2000), the primary motor cortex, BA4 (Basilakos et al., 2015; Graff-Radford et al., 2014), the premotor cortex, BA6 (Graff-Radford et al., 2014; Square-Storer et al., 1997) and the supplementary motor cortex, BA8 (Square-Storer et al., 1997). A lesion in the cerebellum may cause AoS as well (Mariën & Verhoeven, 2007; Mariën, Engelborghs, Fabbro, & De Deyn, 2001; Mariën et al., 2006; Mariën et al., 2014). Thus, aphasia and AoS can both be caused by lesions in many areas. The cortical brain regions that are involved in aphasia and AoS are depicted in Figure 1.8.

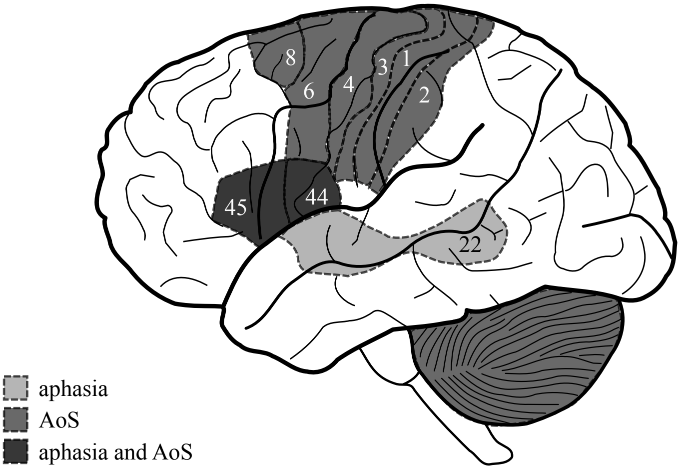


Figure 1.8: Cortical brain regions that are involved in aphasia (depicted in light grey), AoS (depicted in medium grey) and in both aphasia and AoS (depicted in dark grey). Brain regions are numbered according to Brodmann's system. The shapes of the Brodmann Areas in the figure are adapted from Noback et al. (2005) and the shape of the brain is from https://upload.wikimedia.org/wikipedia/commons/0/04/Human_Brain_sketch_with_eyes_and_cerebellum.svg.

EEG can help to trace when errors in spoken word production arise. In several studies, Laganaro and colleagues have shown that the impaired speech production stage can be detected by comparing the EEG data of individuals with aphasia and individuals with AoS to the EEG data of non-brain-damaged individuals in the time window corresponding to the impaired speech production stage. Groups of patients have been compared to a group of age-matched non-brain-damaged controls, because it is not good practice to directly compare groups of patients to one another, unless their lesion site and size is identical. In these studies, EEG was recorded as speech production tasks were carried out, such as picture naming (Laganaro et al., 2009; Laganaro, Morand, Michel, Spinelli, & Schnider, 2011; Laganaro, Python, & Toepel, 2013; Laganaro, 2011), word reading (Laganaro et al., 2013) and nonword reading (Laganaro, 2011). The EEG data of individuals with a semantic impairment differed from that of non-brain-damaged individuals from 110 to 430 ms after stimulus presentation (Laganaro et al., 2009). From 290 to 430 ms after stimulus presentation, individuals with an impairment in lexical retrieval[4] differed from non-brain-damaged individuals. The onset of a difference between individuals with phonological and/or phonetic impairment due to aphasia

[4] According to the definition used by Laganaro et al. (2009), phonological encoding comprises the stages that are referred to as lexeme retrieval and phonological encoding in the current study. The individuals with a phonological disorder described in the study by Laganaro et al. (2009) have an impairment in the retrieval of the phonological word form, thus in lexical retrieval in our terminology. The time window in which the EEG of the individuals with a lexical disorder and the non-brain-damaged adults differed corresponds to the time window of the lexical frequency effect observed in non-brain-damaged individuals in the same study, which has an effect on lexeme retrieval.

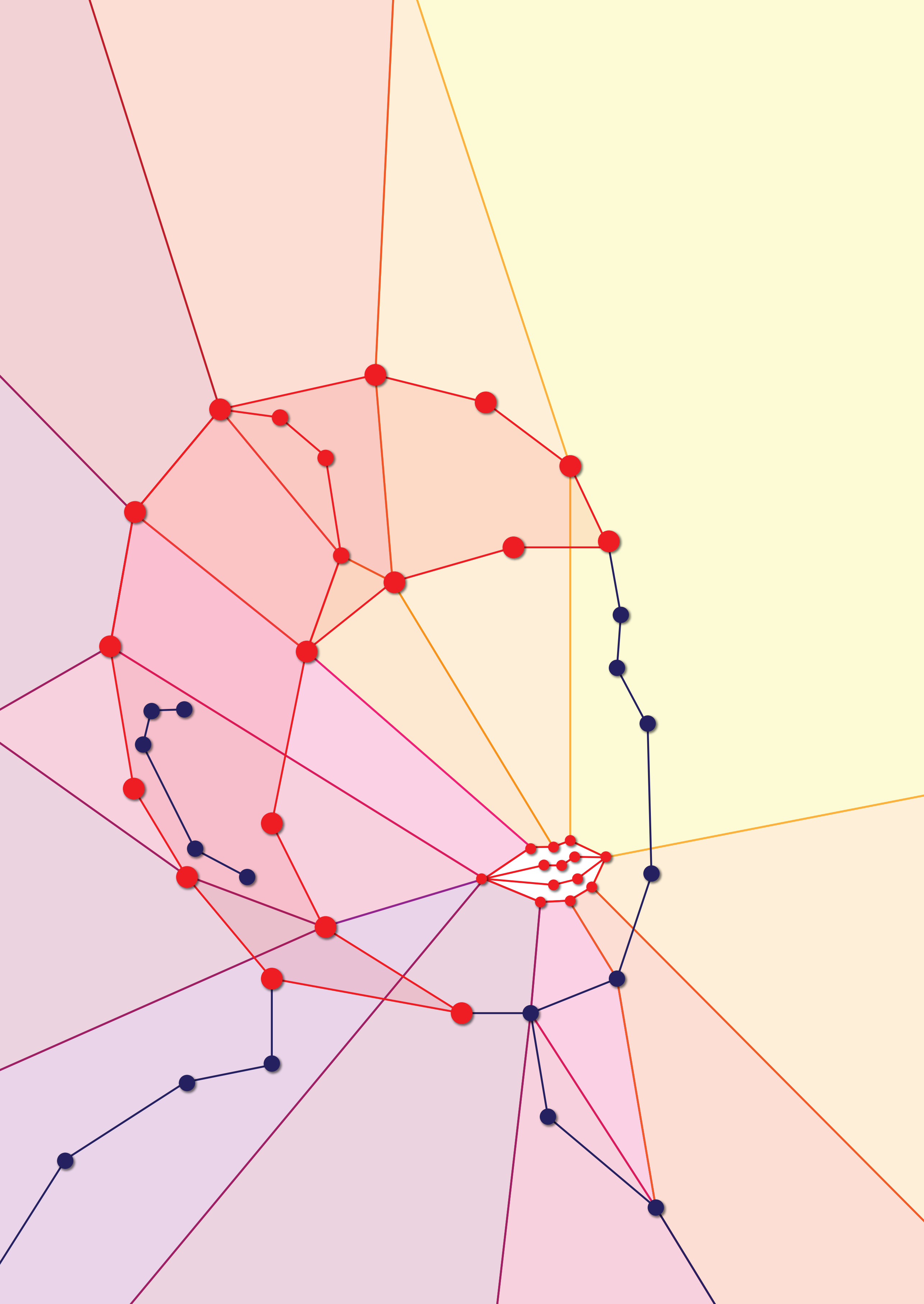
and/or AoS and non-brain-damaged individuals has been identified in the EEG data at around 400 ms after stimulus presentation in a picture naming task and at around 320 ms after stimulus presentation in a word reading task (Laganaro et al., 2013). However, a phonological impairment could not be distinguished from a phonetic impairment by using EEG in this study. In another study, individuals with a phonetic impairment due to AoS have been found to differ from non-brain-damaged adults starting around 300 ms before response onset in the EEG data (Laganaro, 2011).

EEG data not only reflects the time window of the impaired stage, but also the severity of the disorder. The differences between individuals with mild aphasia and non-brain-damaged individuals were considerably smaller and shorter than the differences between individuals with a more severe aphasia and non-brain-damaged individuals (Laganaro et al., 2009). Furthermore, a comparison of the EEG data recorded during the same naming task, carried out before and after a stroke causing aphasia in one individual, showed a difference between the pre- and post-stroke data in the time window associated with the stage hypothesized to be impaired (Laganaro et al., 2011).

1.3 Issues addressed in this dissertation and outline

AoS is usually accompanied with aphasia (Nicholas, 2005). This makes it hard to distinguish between aphasic individuals with a predominant impairment at the level of phonological encoding on the one hand and aphasic individuals with AoS (an impairment at the level of phonetic encoding), on the other hand, because the error patterns overlap. The location of the lesion does not help to identify the impaired stage of speech production, because lesions due to a stroke are usually large and relevant overlapping brain regions may be damaged in both disorders. EEG seems to be a promising method to identify the time window of impaired semantic, lexical and phonological and/or phonetic encoding stages in aphasia as well as the time window of impaired phonetic encoding in AoS (Laganaro et al., 2009; Laganaro et al., 2011; Laganaro et al., 2013; Laganaro, 2011). The goal of this thesis is to distinguish individuals with a phonological encoding disorder from individuals with aphasia and AoS by using EEG. Specifically, EEG will be used to identify the level of impairment in individuals who produce phonemic errors. Therefore, their EEG data will be recorded during word and nonword production tasks and compared to the EEG data of non-brain-damaged speakers recorded during the same tasks.

The structure of the thesis is as follows. In Chapter 2, the protocol used to track lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding will be presented. This is the first study in which these four speech production stages are studied in one group of individuals simultaneously. This proof of principle study of the protocol has been carried out with neurologically healthy young adults. The aim of the proof of principle study is to test whether the four stages can be identified using the protocol. The time course of the speech production stages in older neurologically healthy adults will be described in Chapter 3. The aims of that study were to test whether the protocol can be used to track the speech production stages in older adults as well as whether the speech production stages change with age (Den Hollander, Jonkers, Mariën, & Bastiaanse, 2019). A comparison of the speech production stages between the younger and the older adults will be made. In Chapter 4, the manifestation of speech production stages in individuals with aphasia and a phonological disorder and in individuals with both aphasia and AoS will be compared to the manifestation of these stages in age matched neurologically healthy adults. The aim of the study described in Chapter 4 is to distinguish individuals with aphasia and a phonological encoding disorder from individuals with aphasia and AoS by using EEG. A general discussion of the main findings is presented in Chapter 5.



Chapter 2

Tracking the speech production stages of word and nonword production in adults by using EEG

2.1. Introduction

This chapter uses an EEG protocol to track the speech production stages of lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding in neurologically healthy adults. The protocol is optimal to identify the timing of the four stages, because the stages were tracked in one and the same group of adults. The EEG data were measured from all scalp electrodes and analyzed for the full time course of speech production.

2.1.1 Model of spoken word production

While we are speaking, many processes take place in our brain. These processes can be linked to speech production stages in a model of spoken word production, such as the one by Levelt and colleagues (e.g. Indefrey & Levelt, 2004; Levelt, Roelofs, & Meyer, 1999). The model can be used to describe the process of naming a picture, such as a picture of a rose. An example is provided in Figure 2.1[5]. Picture naming starts with recognizing the object: for a rose, a drawing in black ink on a white background in the shape of a thorny branch with a leaf on the side and many petals at the top of the branch (see 1 in Figure 2.1). This description is used to access the concept ROSE (2). The concept activates the target lemma node ROSE and co-activates semantically related neighboring nodes, such as TULIP and DAISY (3). The target node receives the highest activation. Thus, the target lemma *rose* is retrieved from the mental lexicon (4). Then, the word form or lexeme /roʊs/ (5) is accessed in the lexicon. The phonemes corresponding to the lexeme, /r/, /oʊ/ and /s/, are recruited and ordered. The retrieved phonemes are combined into syllables and the stress pattern of the phonological word is assigned (6). Thereafter, the syllables are translated or 'phonetically encoded' into an articulatory program that specifies the movements of the muscles that are involved in the articulation of speech sounds that form the word (7). During exhalation, the articulation program is carried out by muscles that modify the airflow from the lungs into the nasal and oral cavity by adjusting the level of obstruction at the vocal cords. Also, the airflow is adjusted by the shape of the tongue and the lips. The word "rose" is spoken (8).

2.1.2 Timing of spoken word production stages

The process from picture recognition to spoken word production can be completed in less than one second. Several variables have an effect on particular speech production stages: imageability (e.g. Nickels, 1995), semantic interference (e.g. Howard, Nickels, Coltheart, & Cole-Virtue, 2006) and lemma frequency (e.g. Bastiaanse, Wieling, & Wolthuis, 2016) have an impact on lemma retrieval, word frequency (e.g. Jescheniak & Levelt, 1994) and age of acquisition (AoA) influence lexeme retrieval (e.g. Bastiaanse et al., 2016), word length has

[5] Note that the structure of the model corresponds to the model by Indefrey & Levelt (2004), while the terms 'lemma retrieval' and 'lexeme retrieval' that are used in Figure 2.1 differ from the terms 'lexical retrieval' and 'morpho-phonological code retrieval' that were used by Indefrey & Levelt (2004).

an effect on phonological encoding (e.g. Nickels, 1995) and syllable frequency influences phonetic encoding (e.g. Laganaro & Alario, 2006). These variables can be manipulated in speech production tasks to tap into a particular process by using EEG or MEG. In this way, the timing of an effect elicited by such a variable can be used to track the time window of the speech production stage. Table 2.1 provides an overview of the variables that have been used to track lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding in EEG and MEG studies along with the timing of the effects that were reported.

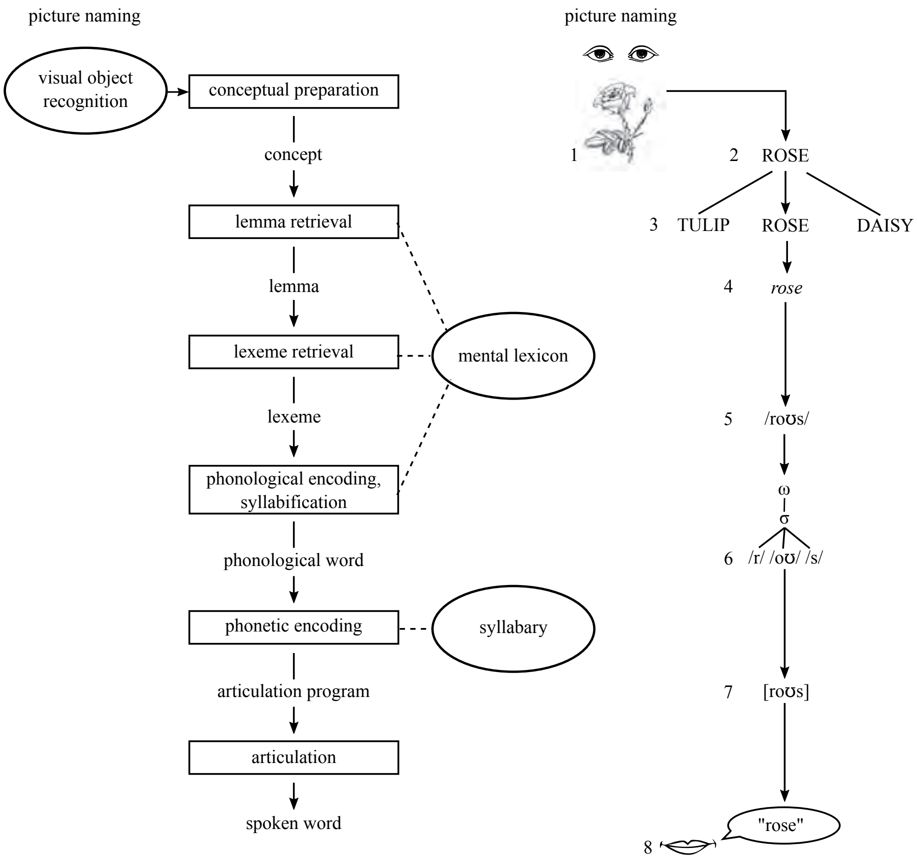


Figure 2.1: The process of picture naming in a model of spoken word production based on Levelt et al. (1999) and Indefrey and Levelt (2004). Boxes represent stages. An example for naming the picture of a rose is provided next to the model.

Indefrey (2011) estimated the time course of the speech production stages based on analysis of the results of several EEG and MEG experiments. He reported time windows from 200 to 275 ms after stimulus presentation for lemma retrieval, from 275 to 355 ms for lexeme retrieval, from 355 to 455 ms for phonological encoding - its duration increases as word length increases - and from 455 to 600 ms after stimulus onset for phonetic encoding. The time windows of the stages do not overlap. This is in line with the serial concept of the model by Levelt et al. (1999): once the previous stage is completed, the next stage starts. However, as can be seen in Table 2.1, the time windows in which effects related to lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding have been identified in EEG and MEG studies do in fact show some overlap. Such an overlap can be explained by interaction between the stages, as suggested, for example, by Dell (1986; Dell, Burger, & Svec, 1997). According to the results of the studies in Table 2.1, lemma retrieval starts as early as around 100 ms rather than around 200 ms as Indefrey (2011) reported. Early lemma retrieval is supported by an EEG study using a picture classification task. The brain can distinguish animals from cars starting 92 ms after stimulus onset (VanRullen & Thorpe, 2001). Also, by 120 ms after stimulus presentation, objects can be fully differentiated (Contini, Wardle, & Carlson, 2017). Therefore, it is possible that semantic information is available even earlier than 100 ms after stimulus presentation. EEG and MEG studies have shown effects related to lemma retrieval from 106 to 550 ms after stimulus onset, effects related to lexeme retrieval from 120 ms after stimulus presentation to 100 ms before response onset, effects related to phonological encoding from 200 ms after stimulus presentation to 120 ms before response onset and effects related to phonetic encoding from 300 to 100 ms before response onset. The overlap of these time windows can be explained by the fact that ranges were computed over the results of several studies. In these studies, various paradigms and factors were used to manipulate the speech production process at a certain stage, which may have influenced the time window in which the effect was found. However, the reported timing of the AoA effect was also not identical in the three studies in which the same picture naming task was used (Laganaro & Perret, 2011; Laganaro, Valente, & Perret, 2012; Valente, Bürki, & Laganaro, 2014). The difference in timing can be explained by variation between participants. Whether participants are slow or fast speakers has an impact on the AoA effect (Laganaro et al., 2012). Therefore, it is important to differentiate the stages in the same group of participants. Also, the time windows that were selected for the analysis differed across studies. Predefined time windows after stimulus onset (e.g. Maess et al., 2002) but also data-driven time windows after stimulus onset (stimulus-locked) and before response onset (response-locked) (e.g. Bürki, Pellet-Cheneval, & Laganaro, 2015) have been analyzed. Finally, the region on the scalp where effects have been measured varied between the studies. If a frontal brain region is involved in a process, but only a central region is included in the analysis, the effect may be registered later at central sites as compared to when the effect was measured at frontal sites.

Table 2.1: Variables that have been used to track lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding in EEG and MEG studies. The first row of each stage contains the timing in ms from Indefrey (2011) and the second row presents the time range of the stage in ms based on the literature listed in the table.

Variables and publications	Onset (ms)	Offset (ms)
Lemma retrieval		
Indefrey (2011)	200	275
Range in relevant studies	106	550
In picture naming tasks		
Cumulative semantic interference effect[6]		
Costa, Strijkers, Martin, & Thierry (2009)	200	380
Maess, Friederici, Damian, Meyer, & Levelt (2002)	150	225
Picture-word interference paradigm		
Aristei, Melinger, & Abdel Rahman (2011)	200	550
Hirschfeld, Jansma, Bölte, & Zwitserlood (2008)	120	220
with semantic distractor words		
Dell'Acqua, Sessa, Peressotti, Mulatti, Navarette, & Grainger (2010)	106 & 320	n.a.
High versus low lemma frequency		
Strijkers, Costa, & Thierry (2010)	180	n.a.
High (object nouns) versus low (action nouns) imageability		
Fargier & Laganaro (2015)	250	380
Lexeme retrieval		
Indefrey (2011)	275	355
Range in relevant studies	120	100 pre-resp[7]
In picture naming tasks		
High versus low lexeme frequency		
Laganaro, Morand, Schwitter, Zimmermann, Camen, & Schnider (2009)	270	464
Levelt, Praamstra, Meyer, Helenius, & Salmelin (1998)	150	400
Early versus late AoA		
Laganaro & Perret (2011)	120	350
Laganaro et al. (2012)	380	200 pre-resp
Valente et al. (2014)	380	100 pre-resp
Gender and phoneme monitoring		
Camen, Morand, & Laganaro (2010)	270	290
Phonological encoding		
Indefrey (2011)	355	455
Range in relevant studies	321	n.a.
In picture naming tasks		
Word length		
Hendrix, Bolger, & Baayen (2017)	No effect	
Valente et al. (2014)	No effect	
Picture-word interference with phonologically related words		
Dell'Acqua et al. (2010)	321	n.a.
Phonetic encoding		
Indefrey (2011)	455	600
Range in relevant studies	300 pre-resp	100 pre-resp
Syllable frequency in a nonword reading task		
Laganaro (2011)	300 pre-resp	n.a.
with phoneme completion		
Bürki et al. (2015)	170 pre-resp	100 pre-resp

2

6 The cumulative semantic interference effect arises when pictures of semantic neighbors, such as rose and tulip, are to be named shortly after one another. When tulip was recently named, its lemma node is still activated and thus there is more competition between the nodes for rose and tulip. This competition slows down lemma retrieval.

7 Pre-resp means before response onset.

2.1.3 Current study

The aim of the current study was to test whether EEG could be used to identify the stages of lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding in one group of participants at one moment of testing. The manipulations that were used to study the time windows of these stages are described in the remainder of this section. To avoid variability in the time windows of the stages that may be caused by the selection of participants, the same participants were tested in the four experiments described in this chapter. Moreover, differences in the selection of time windows and electrodes included in the analysis cannot influence the results. In each experiment, the full time window from stimulus presentation onset until 100 ms before articulation onset was analyzed in stimulus- and response-locked time windows. EEG data were recorded using 64 electrodes and all electrodes were included in the analysis.

It was hypothesized that the cumulative semantic interference effect (Howard et al., 2006) can be used to track lemma retrieval using a picture naming task. When a picture of a rose is to be named, the lemma node ROSE is activated. Its semantically related neighboring lemma nodes, such as TULIP and DAISY, are co-activated. Nevertheless, ROSE receives most activation and the lemma *rose* will be retrieved. However, if the lemma *tulip* has been retrieved to name a previous picture, the lemma node TULIP will be primed and therefore more active, resulting in greater competition between it and the lemma node ROSE. Thus, lemma retrieval becomes increasingly slowed as the number of previously named items of a semantic category increases, which is referred to as the 'cumulative semantic interference effect'. This effect has been tested in two studies using EEG (Costa et al., 2009; Maess et al., 2002) and was also used to track lemma retrieval in the current study.

The second hypothesis was that lexeme retrieval can be manipulated with a picture naming task in which the lexemes vary in AoA. AoA is the age at which a word is acquired. Naming speed decreases as AoA increases (Morrison & Ellis, 1995; Morrison, Ellis, & Quinlan, 1992). Reported ages are often based on questionnaires in which native speakers were asked at which age they believe to have acquired the word (e.g. Brysbaert, Stevens, De Deyne, Voorspoels, & Storms, 2014). AoA has been linked to lemma retrieval in a semantic interference task (Belke, Brysbaert, Meyer, & Ghyselinck, 2005) and in a semantic categorization task (Johnston and Barry, 2005). However, when naming speed is measured without a semantic manipulation, AoA influences lexeme rather than lemma retrieval (Chalard & Bonin, 2006; Kittredge, Dell, Verkuilen, & Schwartz, 2008; Morrison & Ellis, 1995; Morrison et al., 1992). Also, it has repeatedly been shown in EEG studies that AoA influences lexeme retrieval (Laganaro & Perret, 2011; Laganaro et al., 2012; Valente et al., 2014). In the current study, the AoA effect was used to track lexeme retrieval.

Phonological and phonetic encoding were tested using a nonword reading and a nonword repetition task. Nonwords are valid combinations of phonemes and syllables that do not exist in the tested language. Therefore, nonwords have no matching entries in the mental lexicon, so they cannot be produced via the lexical route in the speech production model. Instead, the sublexical route is used, which is shown in Figure 2.2 with the example 'kikkels'. By using the sublexical route, effects arising during lemma and lexeme retrieval are excluded. The sublexical route uses the same three final stages as the lexical route, that is, phonological encoding (see 4 in Figure 2.2), phonetic encoding (5) and articulation (6). The difference between nonword reading and nonword repetition is the lead-in process to phonological encoding as described in the model by Ellis and Young (1988). For nonword reading (1a), the graphemes <k>,<i>,<k>, <k>,<e>,<l> and <s> (2a) have to be converted to phonemes /k/ /ɪ/ /k/ /ɛ/ /l/ /s/ (3a). During syllabification the phonemes are adjusted for coarticulation, which results in /k/ /ɪ/ /k/ /ə/ /l/ /s/ (4). For nonword repetition the nonword /kɪkəls/ is heard (1b) and its phonemes /k/ /ɪ/ /k/ /ə/ /l/ /s/ are identified (3b) and then need to be retrieved and phonologically encoded. Thus, from phonological encoding on, the same stages are involved in both tasks (see Figure 2.2).

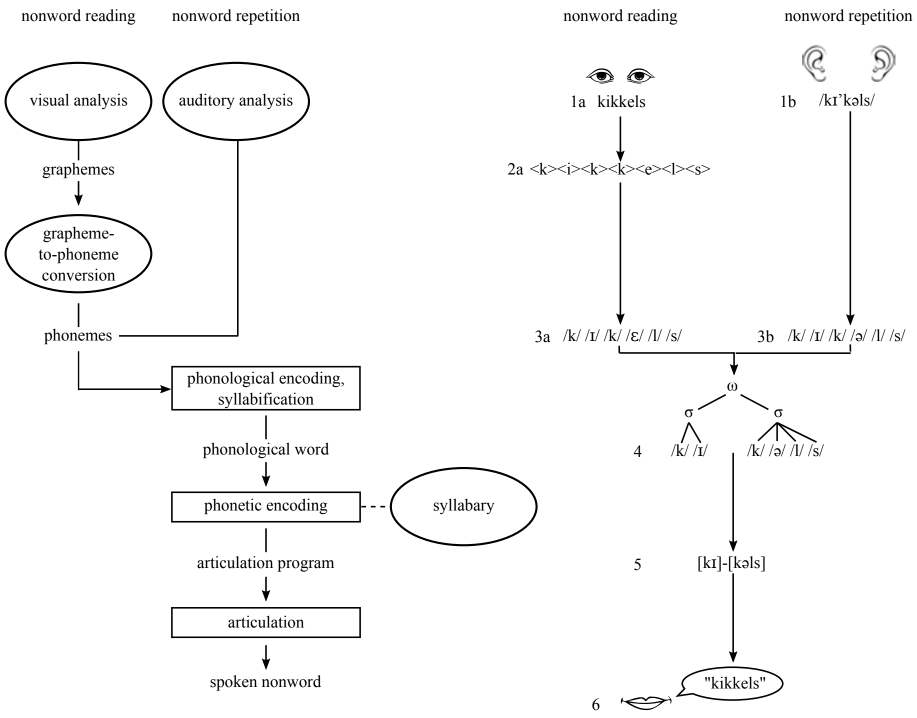


Figure 2.2: The process of nonword repetition and reading in a model based on Ellis and Young (1988) and Indefrey and Levelt (2004). Boxes represent stages. The lead-in processes on top with the stage 'grapheme-to-phoneme conversion' and the storage component on the right are represented as circles. The example for reading and repeating the nonword 'kikkels' is provided next to the model.

Furthermore, it was hypothesized that the length of the nonword in number of phonemes can be used to track phonological encoding. As the number of phonemes in a nonword increases, the number of phonemes for phonological encoding increases, requiring additional processing. Previous EEG studies have found no effect of word length on performance on picture naming tasks (Hendrix et al., 2017; Valente et al., 2014). However, the methodology of the current study was different, because nonwords were used in repetition and reading tasks. In the current study, nonword length in number of phonemes was used to track phonological encoding.

According to Levelt and Wheeldon (1994), articulation programs for high frequency syllables can be retrieved from the syllabary, whereas articulation plans for low frequency syllables need to be computed on demand. Therefore, it was hypothesized that the phonetic encoding of low frequency syllables is more demanding than the phonetic encoding of high frequency syllables. Even though there is much debate about the existence of a syllabary, the effect of syllable frequency on phonetic encoding is widely acknowledged (Cholin, Levelt, & Schiller, 2006; Laganaro & Alario, 2006; Laganaro, 2008). Syllable frequency has previously been used to test for phonetic encoding in two EEG studies (Bürki et al., 2015; Laganaro, 2011). Using EEG, Bürki et al. (2015) found evidence to support the theory by Levelt and Wheeldon (1994) that novel syllables in nonwords and existing, but low frequency, syllables are computed on demand, while high frequency syllables are stored and retrieved. In the current study, syllable frequency was used to detect phonetic encoding using a nonword reading and a nonword repetition task.

This chapter reports a proof of principle study in which it was tested whether four EEG experiments could be used to track the speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding. The design of the experiments is described in this chapter as well as the results of the proof of principle study with a population of young adults. As such, this chapter lays the foundation for the studies in which the protocol is tested in different participant groups described in Chapter 3 (non-brain-damaged speakers varying in age) and Chapter 4 (individuals with aphasia and a phonological disorder and individuals with aphasia and apraxia of speech).

2.2 Methods

2.2.1 Participants

Twenty non-brain-damaged native speakers of Dutch (5 males) participated in the four experiments for a financial compensation (€ 15,00). The mean age of the participants was 21.8 years (age range: 17-28 years). All participants were right-handed, which was confirmed using the short version of the Edinburgh handedness inventory (Oldfield, 1971). They reported no problems in hearing and their vision was normal or corrected to normal. Also, they reported no reading difficulties. All participants, including those who participated in the pretests for the final selection of items, signed an informed consent. The study was approved by the *Ethics Committee of Humanities* of the University of Groningen.

2.2.2 Materials

Lemma retrieval task

The materials used in the lemma retrieval task were black-and-white drawings. The pictures originated from a therapy program (*Auditief Taalbegripsprogramma (ATP)*, Bastiaanse, 2010) and a test (*Werkwoorden- en ActieTest (WAT)*; see Bastiaanse et al., 2016) for individuals with aphasia. The order in which the depicted nouns were presented was manipulated for the cumulative semantic interference effect. The pictures were grouped in sets of five semantically related neighbors (e.g., 'bed', 'couch', 'cradle', 'closet', 'chair') that fit into a particular category (e.g., furniture, clothes, insects). The depicted nouns were all mono- or disyllabic in Dutch. The five nouns within one category had the same number of syllables, the same stress pattern and were controlled for logarithmic lemma frequency in Dutch (Baayen, Piepenbrock, & Gulikers, 1995).

For pretesting the materials, four participants (one male) with a mean age of 22 years (age range: 21-23 years) performed a picture naming task. Items that were named incorrectly by more than one participant were excluded. The 125 items that were included in the final version of the test had an overall name agreement of 91,4%. The overall mean logarithmic lemma frequency was 1.28 (range: 0-2.91). Two lists with reversed conditions were used to avoid an order of appearance effect. Items within one category were not presented right after one another. In both lists, the lag between items within one category ranged between 2 and 12 items, with a mean of 6.27 in List 1 and 6.34 in List 2. The pictures were presented in three blocks of 30 items and one block of 35 items. Some example items are provided in Figure 2.3. The items are provided in Appendix 1.

Pictures were presented on a computer screen and participants were asked to name them in one word as quickly and accurately as possible. Before the picture was presented, a black fixation cross on a white background was shown for 500 ms. The function of the fixation cross was to draw attention and to announce that a picture was presented soon. The picture was shown for 5 seconds.

Lexeme retrieval task

The pictures that were used in the lexeme retrieval task originated from the same source as the materials for the lemma retrieval task. To avoid semantic interference, a maximum of two items per semantic category were included. Dutch mono- and disyllabic nouns were included. Items were controlled for AoA (Brysbaert et al., 2014) and lexeme frequency (Baayen et al., 1995).

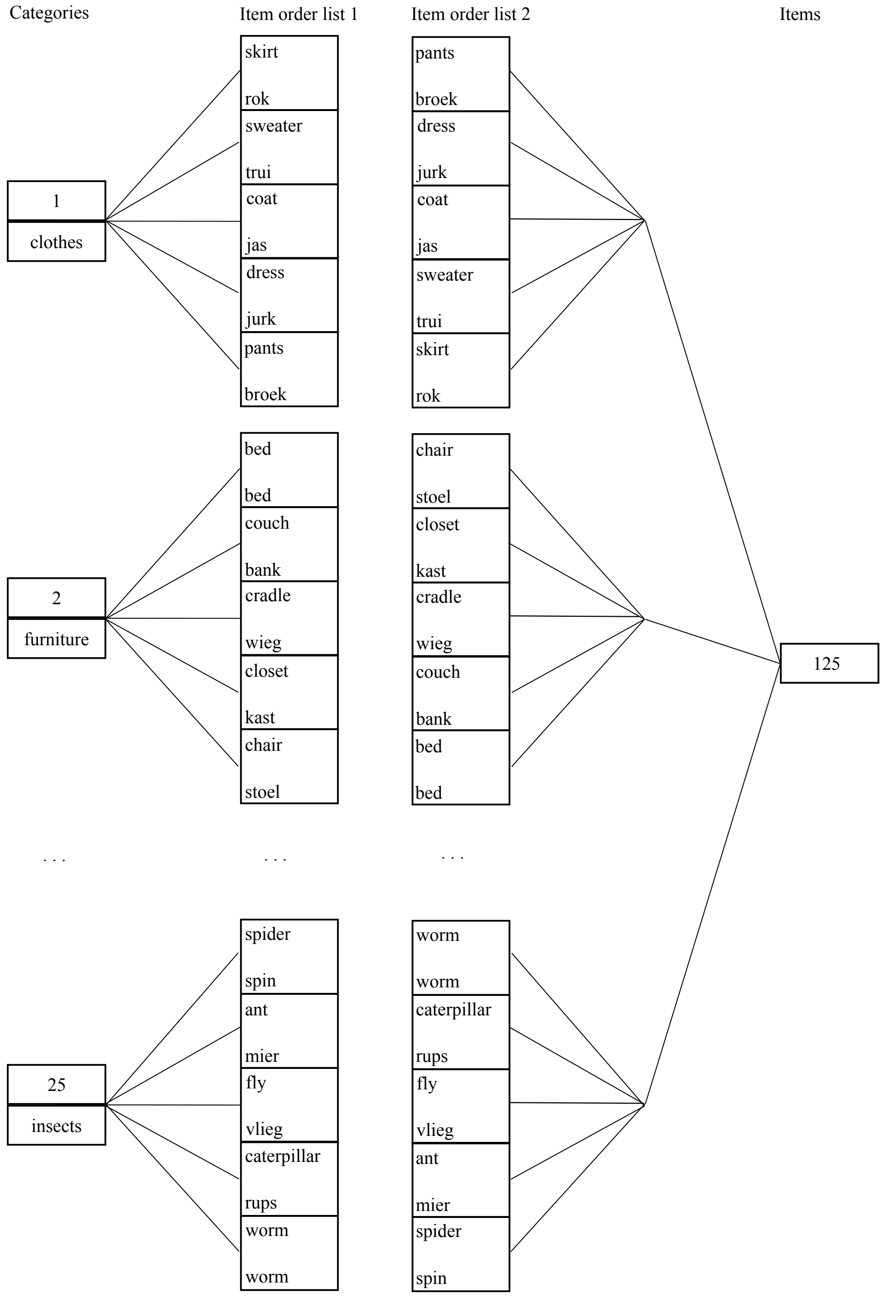


Figure 2.3: Scheme of the 125 selected items from 25 categories (e.g. clothes) and the order of items in List 1 and List 2. The second word in the cells in the center (e.g. 'rok') is the noun in Dutch.

Four participants (one male) with a mean age of 20.7 years (age range 19-22) took part in pretesting the materials in a picture naming task. These participants had not taken part in the pretest of the lemma retrieval task. Items that were named incorrectly by more than one participant were disregarded. The final set of 140 items had an overall name agreement of 93.9%. AoA ranged from 4.01 years for the noun 'book' to 9.41 years for the noun 'anchor', with a mean of 5.96 years. The mean logarithmic lexeme frequency was 1.02 (range: 0-2.44). The correlation between AoA and lexeme frequency in the items was significant (r (138) = -.28, $p < .001$). Therefore, studying both aspects was not required and only AoA has been taken into account. The items were organized in one list including four blocks of 35 items. The order of the items was randomized per block and every participant named the pictures in a different order. The items are provided in Appendix 2.

The procedure of the lexeme retrieval task was the same as the procedure of the lemma retrieval task. Participants were asked to name the pictures as quickly and accurately as possible. Thirty-nine items were used in both the lemma and the lexeme retrieval task, but the two picture naming tasks were never administered consecutively. One of the nonword tasks was always administered in between.

2

Phonological and phonetic encoding tasks

The nonwords that were used for the reading and repetition tasks were disyllabic. They were composed of two existing Dutch syllables, that together resulted in a nonword, e.g. 'kikkels' or 'raalkro'. The frequency of spoken syllables in the nonwords was selected to be between 250 and 5,000 per million syllables (Nederlandse Taalunie, 2004). The frequency range of the syllables used in the nonwords was above the mean spoken syllable frequency for Dutch of 231 per million syllables. Spoken syllable frequency for Dutch ranges from 1 to 410,426 per million syllables. Notwithstanding the fact that the border between high and low syllable frequency was not specified by Levelt and Wheeldon (1994), it was assumed that the frequency of the spoken syllables used in the nonwords was high enough to have the corresponding articulation plans stored in the syllabary. Syllable frequency is known to impact on the retrieval time for stored articulation plans of syllables that are above mean written syllable frequency (Levelt & Wheeldon, 1994).

Two lists of nonwords were developed. Of each list, two versions were created: a written version for the reading task and a version with recorded audio files for the repetition task. The two lists contained the same syllables, but the syllables were combined differently, thus the nonwords were unique.

The nonwords were pretested by the eight participants who did the pretest of the picture naming tasks as well. For each list, two participants carried out the reading task and the other two participants carried out the repetition task. Items that were produced incorrectly by at least one participant were excluded. The 140 selected items for List 1 had an accuracy rate of 100% in both the reading and the repetition task. For List 2, the accuracy rate was 100% for the repetition task. In the reading task, 8% of the nonwords of List 2 were produced incorrectly. The syllables used in these items were combined into new nonwords. These nonwords were pretested in a reading task administered with two native speakers of Dutch. Their accuracy was 100%.

For each nonword, the average spoken syllable frequency was computed over its two syllables. The average syllable frequency computed over the syllables of all 140 items was 1136 per million syllables (range: 257-4514) for List 1 and 1077 per million syllables (range: 257-4676) for List 2. List 1 consisted of 47 nonwords with low, 41 nonwords with moderate and 52 nonwords with high mean spoken syllable frequency. The mean spoken syllable frequencies were respectively 359 (range: 257-479), 705 (range: 515-965) and 2178 (range: 1017-4514) per million syllables. List 2 contained 47 nonwords with low, 43 nonwords with moderate and 50 nonwords with high mean spoken syllable frequency. The mean spoken syllable frequencies were sequentially 359 (range: 257-486), 702 (range: 521-979) and 2075 (range: 1032-4676) per million syllables.

The number of phonemes of each nonword was controlled, because the duration of phonological encoding may increase with the number of phonemes. On both lists, the number of phonemes in the nonwords ranged from 3 to 8. The average number of phonemes was 5.33 for List 1 and 5.29 for List 2. Each list was divided into four blocks of 35 items. The order of appearance of the items was randomized per block. The items are provided in Appendix 3.

For the reading task, nonwords were presented in white letters on a black background on a computer screen. The font type Trebuchet MS Regular was used in a font size of 64 points. The stimulus was presented for 5 seconds and preceded by a fixation cross, that was presented in white on a black background for 500 ms. Participants were instructed to read the nonwords aloud as quickly and accurately as they could. They were either presented with List 1 or List 2.

For the repetition task, the experiment consisted of four blocks of 35 items. A white fixation cross on a black background was presented on the computer screen for 500 ms. As a white speaker symbol on black background appeared on the screen, a nonword was played through headphones. The duration of each nonword was 1 second. This was followed by a white microphone symbol that was presented on black background for 5 seconds. Participants were asked to repeat the nonword as accurately and quickly as they could when the microphone was displayed on the computer screen. The audio files of the stimuli were recorded from a male native speaker of Dutch. Participants who were presented with List 1 on the reading task were presented with List 2 on the repetition task and vice versa. Thus, a participant never was presented with a nonword twice.

General procedure

Participants carried out four tasks: two picture naming tasks, a nonword reading task and a nonword repetition task. There were two different orders: (1) lemma retrieval task; reading task; lexeme retrieval task; repetition task and (2) lexeme retrieval task; repetition task; lemma retrieval task, reading task. Participants with an odd number followed order (1), participants with an even number followed order (2). During the experiments, participants were seated approximately 70 cm from the computer screen. E-Prime (E-Prime 2.0, 2012) was used to present the stimuli and to record the response times and the responses. A voice key was used to detect the response times. The responses were recorded using a microphone that was attached to a headset. The audio stimuli for the repetition task were presented through the headphones of the headset. Before the experiment started, participants practiced with five items for the picture naming tasks and with eight items for the nonword reading and repetition tasks. Participants had the opportunity to take a short break between the four blocks of the experiments.

EEG data recording

EEG data were recorded with a 64 Ag/AgCl scalp electrodes (WaveGuard) cap using the ASA-lab system (ANT Neuro Inc., Enschede, The Netherlands). The electrode sites were distributed over the scalp according to 10-10 system (Jasper, 1958). Bipolar electrodes were used to record VEOG, for which the electrode sites were vertically aligned with the pupil and located above and below the left eye. Impedance of the skin was kept below 20 kΩ, which was checked before every experiment. Data were acquired with a sampling rate of 512 Hz and reference was recorded from the mastoids.

2.2.3 Data processing and analysis

Behavioral data

The speech onset times indicated by the voice key were insufficiently exact (see: Den Hollander, Bastiaanse, & Jonkers, 2017), because these measures relied on an intensity threshold of 50 dB that needed to be exceeded when the first phoneme was produced. Whether this intensity threshold was exceeded depended on the first phoneme of the word. This was the case when the first phoneme was a vowel or a bilabial phoneme[8]. The intensity threshold was not always exceeded when the first phoneme was a consonant of another type. Creating a sufficient number of unique stimuli that started with a vowel or a bilabial phoneme was not possible. Also, the intensity varied between responses of the same participant. Therefore, the audio recordings of the participants' responses were used to determine the speech onset time. The speech onset time in each audio file was manually determined using visual inspection of the waveform and the spectrogram and auditory inspection of the sound file in Praat (Boersma & Weenink, 2018). The speech onset times based on the audio files were used as response events in the response-locked EEG analysis. ANOVAs were used for the statistical analysis of the behavioral and item data (R Core Team, 2017).

[8] Articulation of bilabial phonemes involves short closure of the lips, such as /b/ /p/ and /m/.

Trials to which participants responded incorrectly were excluded from the analysis (lemma retrieval task: 6.16%; lexeme retrieval task: 5.18%; nonword reading task: 1.46%; nonword repetition task: 1.17%). Also, responses that included hesitations or self-corrections qualified as errors (lemma retrieval task: 1.48%; lexeme retrieval task: 2%; nonword reading task: 0.46%; nonword repetition task: 0.035%). Then, the distribution of the response times of the correct trials in all participants were visualized in histograms per item. Histograms were created using the sm package in R (Bowman and Azzalini, 2014). Items to which many participants responded unusually fast or slow[9] were excluded from the EEG analysis (lemma retrieval task: 8%; lexeme retrieval task: 18.57%; nonword reading task: 12.14%; nonword repetition task: 12.86%). Fast or slow response times were above or below 1.5 standard deviations from the mean and observed in at least 5 participants, while the response times of the other participants deviated less than 1.5 standard deviations from the mean or deviated more than 1.5 standard deviations from the mean in the opposite direction. This narrow cutoff was chosen to prevent that the timing of the targeted process observed in the EEG data differed largely between items. For the EEG data analysis, it was important that a similar waveform was observed over the same set of electrodes in the same time window in items of the same condition. Thereafter, the average response time was computed over all accepted trials. Trials exceeding this average by 1.4 standard deviations of the mean response time were disregarded.

EEG data

The EEG data were preprocessed using EEGLAB (Delorme & Makeig, 2004) as an extension to MATLAB (2015). After re-referencing to the average reference of the mastoids, the data were filtered with a 50 Hz notch filter to remove electricity noise and band-pass filtered from 0.2 to 30 Hz. Then, the data were resampled to 128 Hz. Independent component analysis on all channels was performed for artifact detection. Artifact components, such as eye blinks, were removed through visual inspection. Also, the effect of component removal on the data was visually inspected. The continuous data were segmented per trial from 200 ms before until 2 seconds after stimulus onset. A baseline correction was applied over the data epochs, using the 200 ms before stimulus onset as a baseline. Then the events of disregarded trials were removed. To study the time window from the stimulus onset until the response onset, both stimulus-locked analyses, in which the time window after stimulus onset is analyzed, and response-locked analyses, in which the backwards time window before the response onset is analyzed, were carried out. For the stimulus-locked analysis, the data epochs were segmented from stimulus onset until one sampling point (8 ms) after the earliest response time. This one extra sampling point was removed before the analysis. The start of the response-locked

[9] Fast response times were faster than 600 ms after stimulus presentation in the picture naming tasks, faster than 500 ms after stimulus presentation in the nonword reading task and faster than 1150 ms after stimulus presentation in the repetition task. Slow response times were slower than 1200 ms after stimulus presentation in the picture naming tasks, slower than 850 ms after stimulus presentation in the nonword reading task and slower than 1450 ms after stimulus presentation in the repetition task.

analysis was determined by subtracting the stimulus-locked time window from the response onset. The accepted trials were coded into two or three conditions for the statistical analysis. The conditions are specified below per experiment. These data were exported from EEGLAB into the format used in FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011), which was used for the statistical analysis. Finally, the structure of the data files was prepared for a cluster based permutation analysis (Maris & Oostenveld, 2007).

The aims of the analyses were to identify the time window of lemma retrieval with the cumulative semantic interference effect, the time window of lexeme retrieval with the AoA-effect, the time window of phonological encoding with the nonword length in phonemes effect and the time window of phonetic encoding with the syllable frequency effect. These time windows were identified using group-level cluster-based permutation analyses carried out over all participants. The cumulative semantic interference effect was computed as the difference between the first and the fifth presented item within a category. AoA, nonword length in phonemes and syllable frequency have an ordinal scale. An ordered nominal scale with three categories was used to test for these effects. This was preferred over using a dichotomous scale, because less information was lost. Levels of conditions requiring less processing were used as a baseline: early AoA, short nonword length in phonemes and high syllable frequency. Comparisons were carried out between the baseline level and two levels requiring extra processing, in other words those with later AoA, increased nonword length in phonemes and lower syllable frequency. The difference between words with an AoA of around 5 years (baseline) and words with an AoA of around 6 years, as well as words with an AoA of around 7 years were used to compute the AoA-effect. The effect of nonword length in phonemes was computed as the difference between nonwords consisting of 4 phonemes (baseline) and nonwords consisting of 5 phonemes, as well as nonwords consisting of 6 phonemes. The difference between nonwords with a high syllable frequency of 1000-1500 (baseline) and nonwords with a moderate syllable frequency of 500-1000, as well as nonwords with a low syllable frequency of 250-500 were used to compute the syllable frequency effect. In every analysis, the number of permutations computed was 5000. The Monte Carlo method was used to compute significance probability, using a 2-tailed paired sample T-test. A family-wise error rate with an α of 0.025 was used to correct for the multiple comparison problem. In the first analysis of every experiment, sampling points in the entire time window from stimulus onset until 100 ms before response onset were tested. When an effect was revealed in this large time window, a smaller time window around the effect was tested once, so a more specific timing of the effect could be reported. An effect was defined as a cluster of at least 5 neighboring electrodes that was observed in one or more consecutive sampling points. The smaller time window was tested on all sampling points of the effect.

2.3 Results

2.3.1 Behavioral results

Participants scored above 90% in all tasks. The percentages of correct responses were 92.4% for the lemma retrieval task, 92.9% for the lexeme retrieval task, 98% for the nonword reading task and 98.8% for the nonword repetition task. The mean, standard deviation and range of the response time data from the four experiments are provided in Table 2.2.

Table 2.2: Response times after stimulus presentation in ms per task. Means (M), standard deviations (SD) and ranges (RNG) are reported as M (*SD*, RNG).

Task	Response times (ms)
Picture naming: lemma retrieval	932 (*216*, 602-1461)
Picture naming: lexeme retrieval	938 (*199*, 626-1440)
Nonword reading: phonological and phonetic encoding	690 (*116*, 502-966)
Nonword repetition: phonological and phonetic encoding	1349 (*129*, 1117-1597)

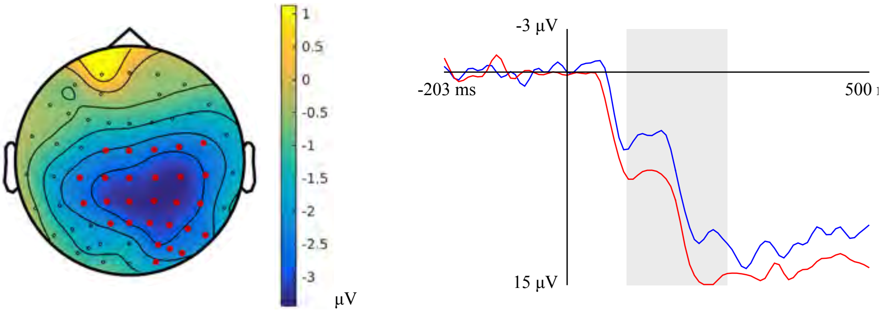
In the lemma retrieval task, an effect of ordinal position on response time was identified ($F(1, 765) = 13.38$, $p < .001$). Increased response times were found for pictures belonging to the same category when they were presented at the fifth ordinal position compared to when they were presented at the first ordinal position. An effect of AoA was identified in the lexeme retrieval task. Response times were found to increase as the AoA of the items advanced ($F(1, 2205) = 104.01$, $p < .001$). In the nonword reading task, an effect of length in number of phonemes was found. Response times were found to increase with increasing number of phonemes in the items ($F(1, 2096) = 5.17$, $p = .017$). In the nonword repetition task, no effect of length in number of phonemes on response time was found ($F(1, 2034) = 2.47$, $p = .1$). Furthermore, an effect of syllable frequency was identified in the nonword reading task. Response time increased as syllable frequency of the items decreased ($F(1, 2320) = 6.35$, $p = .01$). No syllable frequency effect on response time was found in the repetition task ($F(1, 2255) = 0.35$, $p = .5$).

2.3.2 EEG results

The cluster statistic, standard deviation and confidence interval range of all EEG results are provided in Appendix 4. Here we focus on the significant differences between conditions of interest.

Lemma retrieval

A difference between the first and fifth ordinal position was revealed in the latency range from 100 to 265 ms ($p = .005$) after stimulus onset. The difference was most pronounced over right central and posterior sensors. In the response-locked analysis, an effect was found from 445 to 195 ms (p = .004) before response onset. The effect was most pronounced over central and posterior sensors bilaterally and over the right frontal electrodes. The scalp distribution of the stimulus-locked effect and the waveforms of the grand averages for the first and fifth ordinal position are shown in Figure 2.4.



Difference	1st item vs 5th item in ordinal position
Timing	100 - 265 ms post-stimulus onset

grand averages for PO6
1st item in ordinal position = blue
5th item in ordinal position = red

Figure 2.4: Left: the cluster related to the cumulative semantic interference effect that was revealed in the stimulus-locked analysis of the lemma retrieval task. Electrodes included in the cluster are marked in red.
Right: the waveforms of the grand averages for the 1st item (in blue) and 5th item in ordinal position (in red) for electrode PO6. The time window of the effect is highlighted.

Lexeme retrieval

Testing for an AoA effect in the latency range from 100 to 300 ms after stimulus onset, the cluster-based permutation test revealed a difference between the items with an AoA of around 5 years and items with an AoA of around 6 years (p = .002). The difference was present over bilateral frontal and central electrodes. In the response locked cluster-based permutation analysis, a difference between items with an AoA of around 5 years and items with an AoA of around 7 years was revealed from 475 to 330 ms before response onset. The response-locked AoA effect was most pronounced over bilateral frontal and central electrodes ($p < .001$). The scalp distribution of the stimulus-locked effect and its waveforms are shown in Figure 2.5.

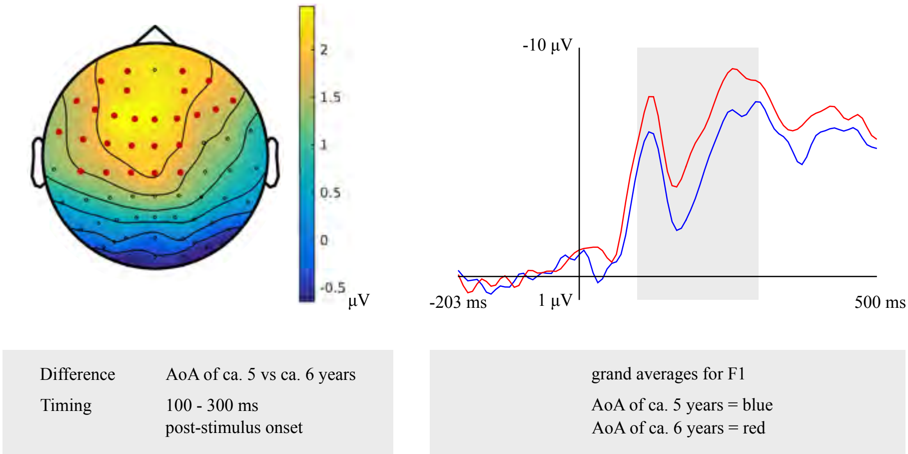


Figure 2.5: Left: the cluster related to the AoA-effect that was revealed in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with an AoA of ca. 5 (in blue) and 6 years (in red) for electrode F1. The time window of the effect is highlighted.

Phonological encoding in the nonword reading task

A stimulus-locked length effect was revealed from 350 to 415 ms for the comparison of nonwords consisting of 4 and 5 phonemes (p= .0032). Also, a stimulus-locked length effect was revealed as a difference between nonwords consisting of 4 and 6 phonemes in a time window from 390 to 425 ms after stimulus presentation (p= .0046). Both stimulus-locked effects were most pronounced over the bilateral centro-posterior electrodes. In the response-locked analysis, a length effect was identified as a difference between 4 and 5 phonemes from 335 to 320 ms before response onset, which was most pronounced over bilateral central and left posterior electrodes (p= .0084). In the response-locked analysis, a length effect as a difference between 4 and 6 phonemes was revealed from 330 to 320 ms before response onset (p= .0084). This effect was most pronounced in right central and bilateral posterior electrodes. The scalp distribution and waveforms of the effect that was registered from 350 to 415 ms after stimulus onset are shown in Figure 2.6.

Phonological encoding in the nonword repetition task

In the stimulus-locked cluster-based permutation analyses, an effect of length was revealed when comparing nonwords consisting of 4 and 5 phonemes from 350 to 410 ms (p = .0062), 530 to 610 ms (p = .001) and from 650 to 750 ms (p = .0006). The effect was most pronounced over bilateral fronto-central electrodes. An effect most pronounced over bilateral centro-posterior electrodes was found for the comparison of nonwords consisting of 4 and 6 phonemes from 935 to 1020 ms after stimulus presentation (p = .0024). Finally, in the response-locked analysis comparing nonwords with a length of 4 and 5 phonemes, an effect was revealed from

580 to 545 ms before response onset (p = .0164). This effect was most pronounced over the right lateralized region. The scalp distribution and waveforms of the effect registered from 650 to 750 ms after stimulus onset are shown in Figure 2.7.

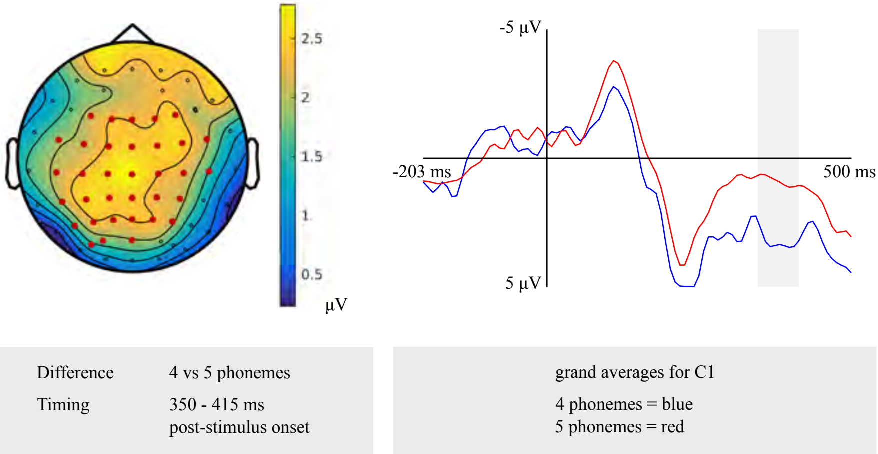


Figure 2.6: Left: the cluster related to the effect of nonword length in phonemes that was revealed in the stimulus-locked analysis of the reading task targeting phonological encoding. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for a nonword length of 4 (in blue) and 5 phonemes (in red) for electrode C1. The time window of the effect is highlighted.

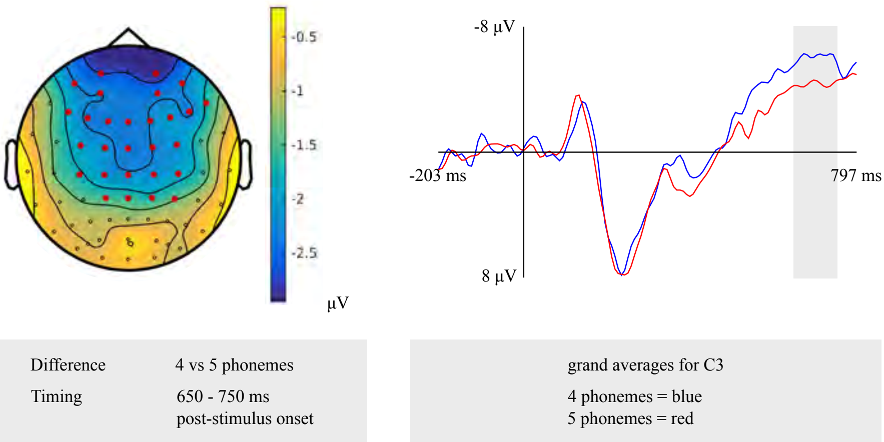


Figure 2.7: Left: the cluster related to the effect of nonword length in phonemes that was revealed in the stimulus-locked analysis of the repetition task targeting phonological encoding. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for a nonword length of 4 (in blue) and 5 phonemes (in red) for electrode C3. The time window of the effect is highlighted.

2

Phonetic encoding in the nonword reading task

Testing for a syllable frequency effect in the latency range from 400 to 450 ms after stimulus onset, the cluster-based permutation test revealed a difference between items with a syllable frequency over 1000 and items with a syllable frequency from 500 to 1000 ($p < .001$). In this latency range, the difference was most pronounced over bilateral central sensors. The second stimulus-locked syllable frequency effect was found between items with a syllable frequency over 1000 and items with a syllable frequency below 500 in the analysis over a time window between 350 and 450 ms after stimulus onset ($p = .01$). The difference was most pronounced over bilateral frontal and central sensors. In the response-locked analysis, a difference between items with a syllable frequency over 1000 and items with a syllable frequency below 500 was revealed in a time window from 250 to 200 ms before response onset ($p = .02$). The effect was most pronounced over bilateral central sensors. The scalp distribution and waveforms of the effect registered from 350 to 450 ms after stimulus onset are shown in Figure 2.8.

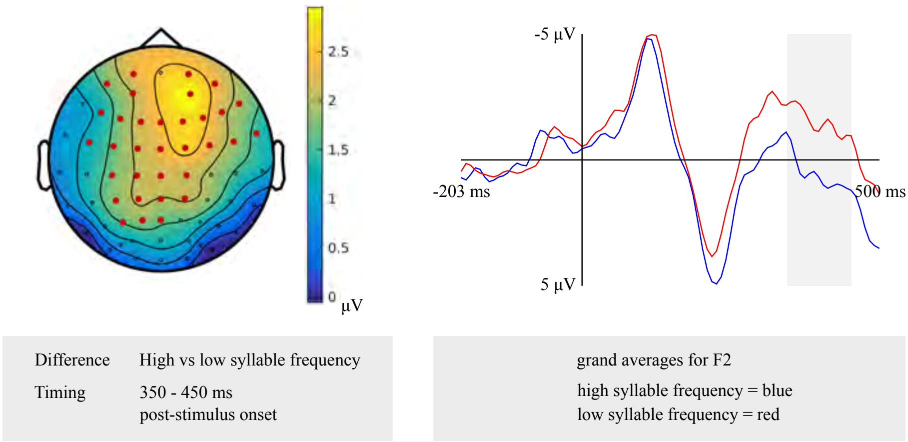


Figure 2.8: Left: the cluster related to the syllable frequency effect that was revealed in the stimulus-locked analysis of the reading task targeting phonetic encoding. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with high (in blue) and low syllable frequency (in red) for electrode F2. The time window of the effect is highlighted.

Phonetic encoding in the nonword repetition task

Testing for a syllable frequency effect in the latency range from 475 to 675 ms after stimulus onset, the cluster-based permutation test revealed a difference between items with a syllable frequency over 1000 and items with a syllable frequency from 500 to 1000 ($p = .003$). The effect was detected over nearly all sensors. Another stimulus-locked syllable frequency effect was found in a time window between 350 and 375 ms. The analysis revealed a difference between items with a syllable frequency over 1000 and items with a syllable frequency below 500 ($p = .02$). The effect was most pronounced over bilateral central sensors. No effect was found in the response-locked analysis. The scalp distribution and waveforms of the effect registered from 475 to 675 ms after stimulus onset are shown in Figure 2.9.

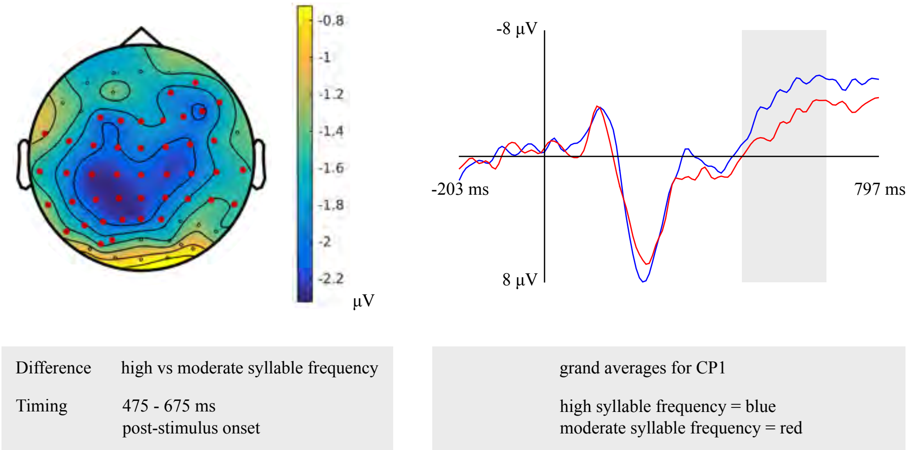


Figure 2.9: Left: the cluster related to the syllable frequency effect that was revealed in the stimulus-locked analysis of the repetition task targeting phonetic encoding. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with high (in blue) and moderate syllable frequency (in red) for electrode CP1. The time window of the effect is highlighted.

2.4 Discussion

While no behavioral differences in response time were found on the nonword repetition task, they were apparent on the lemma retrieval task, on the lexeme retrieval task and on the nonword reading task targeting phonological and phonetic encoding. These differences were also identified in the EEG data. The results will be discussed per stage of the process of spoken word and nonword production. Thereafter, the identified timing of the stages will be discussed in the scope of the speech production model.

2.4.1 Identification of the speech production stages

Lemma retrieval

The cumulative semantic interference effect was used to track lemma retrieval. In the behavioral data, longer response times were found for items within a category that were presented at the fifth ordinal position compared to the items that were presented at the first ordinal position. The time window of lemma retrieval was identified using EEG from 100 to 265 ms after stimulus onset and from 445 to 195 before response onset. No previous study has reported on a response-locked time window for lemma retrieval, thus the response-locked time window identified in the present study cannot be compared to previous findings. The stimulus-locked timing of the cumulative semantic interference effect has been identified in two previous EEG studies (Costa et al., 2009; Maess et al., 2002). The duration of the effect found in the current study was similar to the duration found by Costa et al. (2009). However, in that study, the onset of the effect was 100 ms later. This can be explained by differences in lemma frequency. Similar lemma frequency among the five items of one category was controlled for in the current study. The items used in the study by Costa et al. (2009) were not checked for lemma frequency. Low frequency lemmas are retrieved later than highly frequent lemmas. Therefore, items with low lemma frequency may have caused the lemma retrieval process to be identified in a later time window in that study. The timing of the cumulative semantic interference effect found by Maess et al. (2002) largely overlapped with the timing found in the current study. The onset of the analyzed time window by Maess et al. (2002) was at 150 ms after stimulus presentation, which explains why no earlier effects were reported. In the current analysis, the entire time window from stimulus onset until 100 ms before articulation was studied. Therefore, the effect was revealed earlier than the one in the study by Maess et al. (2002). Our effect was recorded at right central and posterior parts of the scalp. The fact that the EEG data showed activity in the right hemisphere is not uncommon: electric activity generated in one part of the brain can be recorded at parts on the scalp that are quite distant, because electricity spreads out as it moves through the brain and it follows the path of the least resistance (Luck, 2005).

Lexeme retrieval

AoA was shown to influence lexeme retrieval: increased response times were found with increasing AoA. The AoA-effect was used to identify the lexeme retrieval stage using EEG from 100 to 300 ms after stimulus onset and from 475 to 330 ms before response onset. In previous EEG studies, the AoA-effect has been found in varying time windows and with a varying duration, ranging from 120 ms after stimulus presentation up to 100 ms before response onset (Laganaro and Perret, 2011; Laganaro et al., 2012; Valente et al., 2014). The stimulus-locked AoA-effect was comparable to the one identified by Laganaro and Perret (2011), while the response-locked AoA-effect was comparable to the ones found by Laganaro et al. (2012) and Valente et al. (2014). It is clear that comparisons do not always lead to both a stimulus-locked and a response-locked effect. Earlier studies have found either a stimulus-locked effect (e.g. Laganaro & Perret, 2011) or both a stimulus-locked and a response-locked effect (e.g. Laganaro et al., 2012; Valente et al., 2014).

In addition, the onset of the stimulus-locked effect could be thought to be early for lexeme retrieval. However, the effect found by Laganaro and Perret (2011) started only 20 ms later than our effect. Moreover, some authors have suggested that objects are fully differentiated in the brain by 120 ms after stimulus presentation (Contini, Wardle, & Carlson, 2017). Similarly, previous studies have shown that categories of cars and animals can be distinguished before 100 ms (VanRullen & Thorpe, 2001). As the pictures that were used in the present study were black and white drawings that were visually simple, early lexeme retrieval was possible.

Phonological encoding

The effect of nonword length in phonemes was used to target phonological encoding. In the reading task, response times increased with increasing nonword length in phonemes. In the EEG data, this effect was identified from 350 to 425 ms after stimulus presentation and from 335 to 320 ms before response onset. In the repetition task, no effect of length in phonemes on the response time was identified. Hence, it was impossible to interpret the effects in the EEG data. In retrospect, more variation in nonword length in phonemes may have been required to find an effect in the repetition task. This is the first speech production study reporting on nonword length effects using EEG. In previous studies, word length effects have been studied using picture naming tasks and EEG, but no effects have been identified (Hendrix et al., 2017; Valente et al., 2014). The input for phonological encoding of a word differs from the input for phonological encoding of a nonword. Phonological encoding of a familiar lexeme likely requires less effort than the phonological encoding of an unfamiliar string of phonemes. This may explain why the effect was found for nonwords in our study, but not for words in previous studies.

Phonetic encoding

Phonetic encoding was identified using a syllable frequency effect. In the reading task, response times increased as syllable frequency decreased. In the EEG data, the syllable frequency effect was identified from 350 to 450 ms after stimulus onset and from 250 to 200 ms before response onset. The response-locked effect corresponds to the finding by Laganaro (2011), who identified a syllable frequency effect using a nonword reading task that started around 300 ms before response onset. A much later syllable frequency effect, from 170 to 100 ms before response onset, was identified by Bürki et al. (2015). The task used by Bürki et al. (2015) included inserting phonemes into nonwords before the nonwords were read. The complexity of this task can account for the later timing of the syllable frequency effect that was found by Bürki et al. (2015) compared to the current study. Previous studies have found response-locked effects for syllable frequency (Bürki et al., 2015; Laganaro, 2011). We only found a response-locked effect for the comparison between the high and low frequency conditions; the comparison of the high and moderate conditions failed to reach significance. It is probably that the larger difference in frequency between the two conditions made the effect stronger.

In the nonword repetition task, the response times did not reveal a syllable frequency effect. Our EEG results were not interpreted, because of the absence of behavioural effects. In retrospect, including nonwords with a syllable frequency below the mean syllable frequency for Dutch may have been required to find an effect in the repetition task.

2.4.2 Stages in the model of speech production

A summary of the timing of the speech production stages identified using the protocol is shown in Figure 2.10.

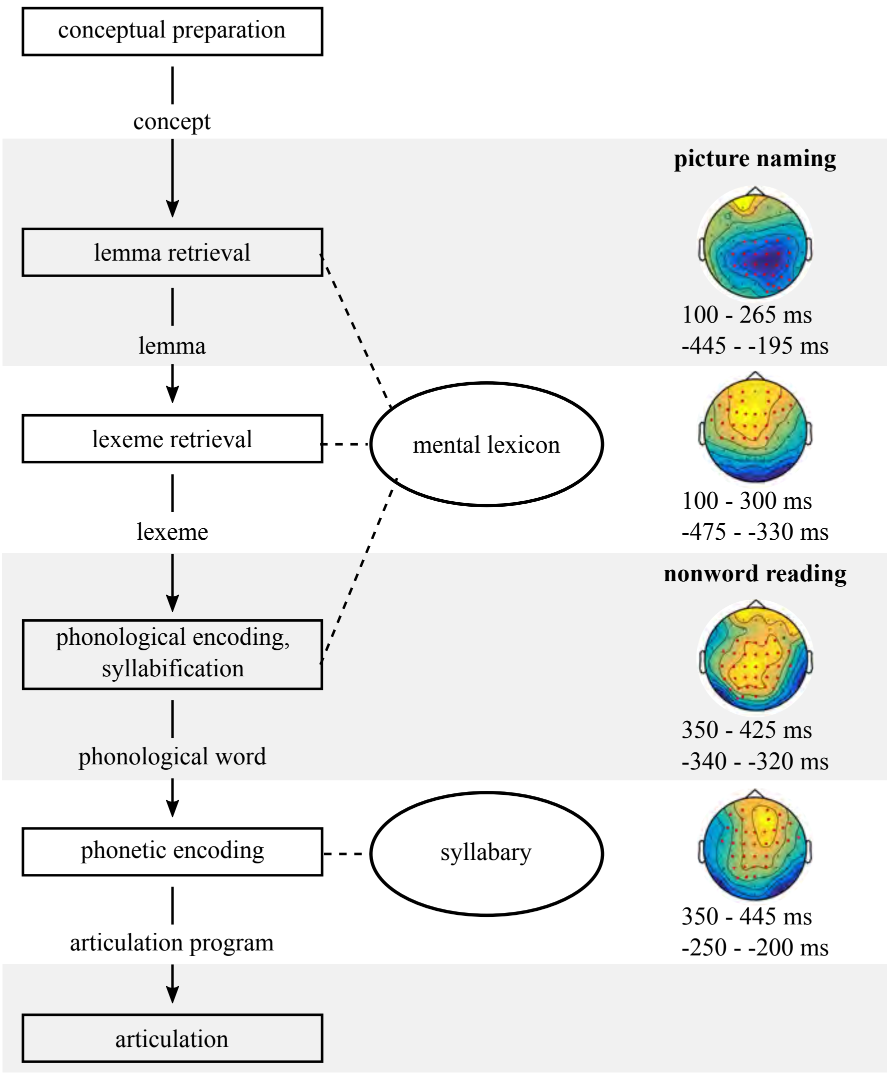


Figure 2.10: The model of spoken word production (Indefrey and Levelt, 2004; Levelt et al., 1999) completed with the timing of the speech production stages identified using the protocol.

Lemma and lexeme retrieval

Indefrey (2011) estimated the timing of lemma retrieval from 200 to 275 ms after stimulus onset, but Maess et al. (2002) and others (e.g. Hirschfeld et al., 2008; Levelt et al., 1998; Stijkers et al., 2010) have shown effects related to lemma retrieval starting earlier than 200 ms after stimulus onset. Strijkers et al. (2010) found an effect of lemma frequency that started 180 ms after stimulus onset. Also, Hirschfeld et al. (2008) identified the timing of lemma retrieval starting at 120 ms after stimulus onset, using a word-picture-interference task. Levelt et al. (1998) defined the time window up to 150 ms after stimulus onset as a stage of visual processing and accessing the lexical concept in an MEG study. An EEG study on visual categorization showed that the brain can distinguish animals from cars 92 ms after stimulus onset (VanRullen & Thorpe, 2001). Thus, visual processing is completed and access to the semantic category of the lexical concept is granted before the first 100 ms are over. Animals and cars are visually distinct. Hence, these categories could have been distinguished using visual attributes rather than lexical concepts. Accessing the full meaning of the lexical concept and mapping this onto a lemma may not have been required in the task by VanRullen and Thorpe (2001). The pictures used in our study were visually distinct as well, even within a category. For example, the category insects contained a fly and caterpillar and the category of toys contained a sandbox and a slide. This may explain early object recognition. Regardless whether full access to the meaning was required for the visual categorization task by VanRullen and Thorpe (2001), visual object recognition may have led to accessing the lexical concept in their study, which in turn may have activated the lemma. Since the pictures that were used in the current study were checked for visual complexity, no differences between conditions were found before 100 ms. As soon as participants had access to the lemma level, the neighboring lemma nodes were competing. Thus, it is likely that lemma retrieval started around 100 ms after stimulus onset.

The time window for lexeme retrieval given by Indefrey (2011) lasts from 275 to 355 ms after stimulus presentation. This time window for lexeme retrieval starts after lemma retrieval, which is in line with the suggestion by Levelt et al. (1999) that the stages are discrete. In the current study, identical onset times were found for lemma and lexeme retrieval. When older adults were tested with the same protocol, an earlier onset was observed for lemma retrieval than for lexeme retrieval (Den Hollander, Jonkers, Mariën, & Bastiaanse, 2019). Hence, if there was a difference in the onset of the lemma and lexeme retrieval stages, our method would have been sensitive enough to detect it. The overlap in the timing of the stages suggests that the stages are not entirely serial, in line with other theories which propose interaction between different levels of processing (e.g., Dell, 1986; Dell et al., 1997). Two studies from one lab also have found identical onset times for lemma retrieval, identified with the cumulative semantic interference effect (Maess et al., 2002), and lexeme retrieval, tested with the lexeme frequency effect (Levelt et al., 1998). In the current study, the items on the picture naming task targeting lemma retrieval were controlled for lemma frequency and the items on the picture naming task targeting lexeme retrieval were controlled for lexeme frequency. Lemma frequency is the summed frequency of all word forms with the same word stem (e.g., cat, cats, cat's) and lexeme frequency is the frequency of the word (e.g. cat). All items were uninflected nouns, meaning that the target word was identical to the word stem. The word stem is stored in the mental lexicon and inflection takes place during grammatical encoding (e.g. Bock & Levelt, 1994; Levelt, 1989; Levelt et al., 1999). Thus, lemma frequency has an impact on lemma retrieval, but Jescheniak and Levelt (1994) have found that word frequency effects originate from lexeme frequency and not from lemma frequency. It has been argued that the AoA-effect influences both lemma and lexeme retrieval. Previous studies have found an effect of AoA on lemma retrieval, but only when the task involved a semantic manipulation (Belke et al., 2005; Johnston and Barry, 2005). However, the absence of a semantic manipulation shows that AoA influences lexeme retrieval (Chalard & Bonin, 2006; Kittredge et al., 2008). In the current study, there was no semantic manipulation to influence the results, because a maximum of two items per semantic category were included. Also, the semantic manipulation of the lemma retrieval experiment cannot have influenced the results: ten out of twenty participants were administered with the lexeme retrieval task before the lemma retrieval task. Furthermore, one of the nonword tasks was administered between both picture naming tasks. Despite the overlap in timing for lemma and lexeme retrieval, EEG can still be used to distinguish the stages, because the electrodes over which the effect was found differ. While the effect related to lemma retrieval was most pronounced over right central and posterior electrodes, the effect related to lexeme retrieval was found over electrodes covering the bilateral fronto-central regions.

Phonological and phonetic encoding

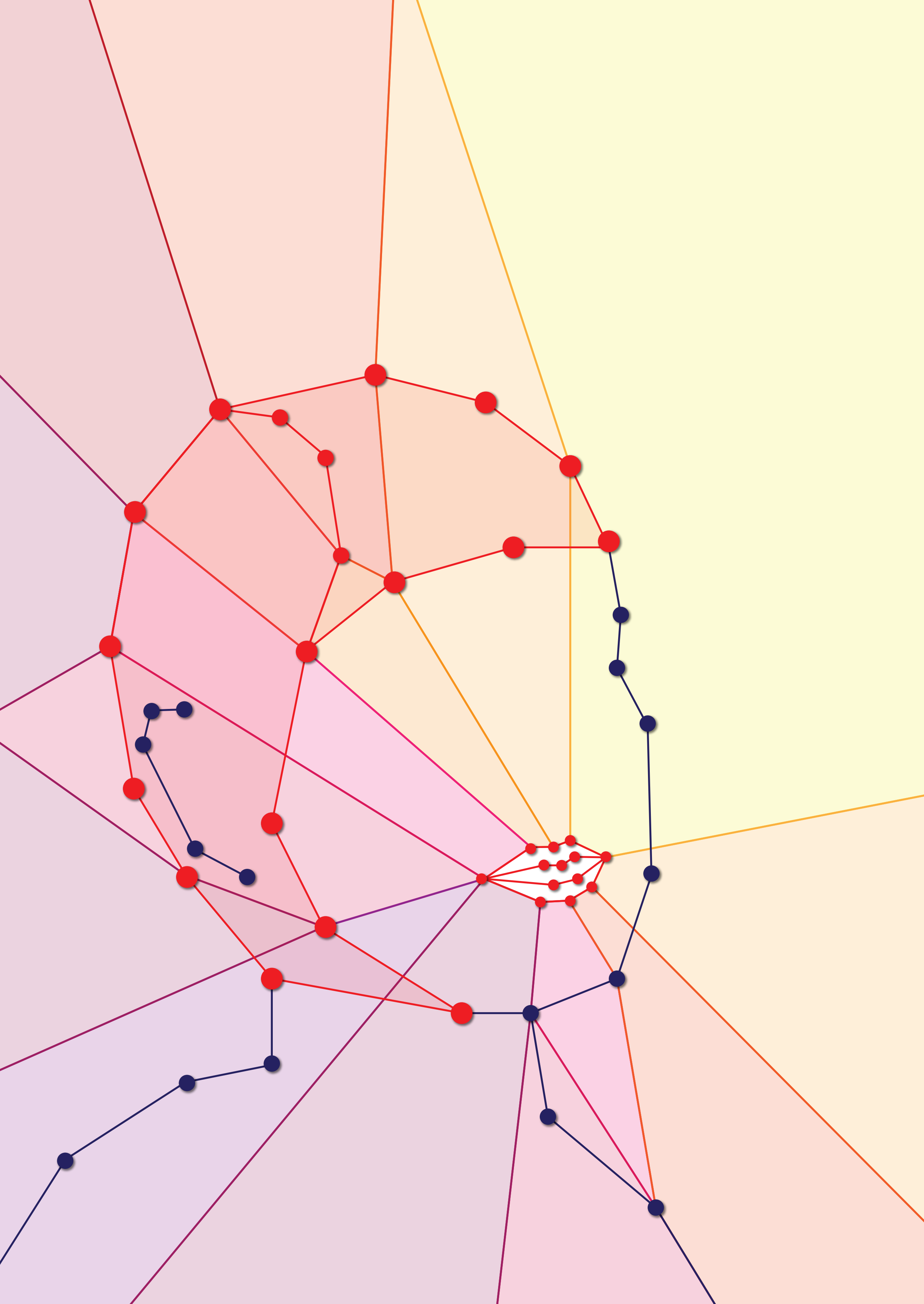
The timing of lemma and lexeme retrieval cannot be compared to the timing of phonological and phonetic encoding, because the route for nonword reading is different from the one used for naming. In the model of spoken word production (Levelt et al., 1999), phonological encoding is preceded by lemma and lexeme retrieval during picture naming. Nonwords are not part of the lexicon and, therefore, lemma and lexeme retrieval do not play a role in the production of nonwords (Ellis & Young, 1988).

According to Indefrey (2011), the timing for phonological encoding is from 355 to 455 ms after stimulus presentation. Thereafter, phonetic encoding takes place from 455 to 600 ms after stimulus presentation. However, in the reading task of the current study, the stimulus-locked effect of nonword length in phonemes targeting phonological encoding started at the same time as the syllable frequency effect targeting phonetic encoding. When older adults were tested using the same protocol, phonological encoding had an earlier onset than phonetic encoding (Den Hollander et al., 2019). Thus, our method would have been sensitive enough to identify a difference in the onset of the timing of the stages. The finding that phonetic encoding started before phonological encoding was completed suggests that the processes interact (Dell, 1986; Dell et al., 1997). Phonological and phonetic encoding are not discrete according to Levelt et al. (1999): phonetic encoding starts as soon as a syllable is phonologically encoded, regardless of whether phonological encoding of the entire word has been completed. In line with Indefrey (2011), phonological encoding ended before phonetic encoding in the stimulus-locked analysis in the reading task. Also, phonological encoding started before phonetic encoding in the response-locked analysis in the reading task.

The response time data of the repetition task revealed no effects of nonword length in phonemes or syllable frequency. Interpreting EEG results without a behavioural effect is unwise. Therefore, the repetition task seemed not to be suitable for differentiating between phonological and phonetic encoding. Hence, this task was removed from the protocol.

2.5 Conclusion

In this study, the speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding were successfully identified using EEG within a group of neurologically healthy speakers. The cumulative semantic interference effect targeting lemma retrieval and the AoA-effect targeting lexeme retrieval were identified in the response time data and in the EEG data recorded during picture naming tasks. Both effects were found to partially overlap, which suggests that lemma and lexeme retrieval are not entirely discrete stages, as Levelt et al. (1999) proposed, but that the stages may interact, like Dell (1986; Dell et al., 1997) suggested. Lexeme retrieval was found to last longer than lemma retrieval, which is in line with the model of spoken word production. In the nonword reading task, effects of nonword length in phonemes and syllable frequency were found in the response time data and in the EEG data, identifying the stages of phonological and phonetic encoding. Both stages were found to start at the same time, but phonetic encoding was found to last longer than phonological encoding. Once again, this suggests that these stages are not fully serial, given the overlap between the stages. Possibly, phonetic encoding of the first syllable starts already during phonological encoding of the second (incremental processing; see Levelt, 1989), and/or the processes interact (Dell, 1986; Dell et al., 1997). In the response-locked analysis, phonological encoding was found to precede phonetic encoding, corresponding to the model of spoken word production. In the repetition task, no effects of nonword length in phonemes or syllable frequency were found in the response time data. Hence, the effects found in the EEG data were not interpreted. Therefore, the repetition task seemed not to be suitable to distinguish phonological from phonetic encoding and was removed from the protocol. The next chapter reports a test of whether these time windows are influenced by the participants' age.



Chapter 3

Identifying the speech production stages in early and late adulthood by using EEG

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https://doi.org/10.3389/fnhum.2019.00298
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3.1 Introduction

3.1.1 Effects of aging on the brain

Structural changes in the brain, such as a reduction of cortical thickness, (Freeman et al., 2008; Zheng et al., 2019), a decrease in the number of cortical folds (Zheng et al., 2019) and a reduction of grey (Freeman et al., 2008) and white matter (Marner et al., 2003) take place throughout one's lifetime. Also, the connectivity within the Cingulo-Opercular Network (CON, including dorsal anterior cingulate, medial superior frontal cortex, anterior insula, frontal operculum and anterior prefrontal cortex (Dosenbach et al., 2007)) and the Fronto-Parietal Control Network (FPCN, including the lateral prefrontal cortex, anterior cingulate cortex and inferior parietal lobule (Vincent et al., 2008)) reduces with aging (Geerligs et al., 2015). These networks modulate higher cognitive functions involved in language processing, such as working memory and reading. While the global efficiency of the three networks is the same in older and younger adults, the local efficiency and the modularity decreases with aging. This decrease may delay the speech production process; however, the efficiency of the visual network, which is used when watching pictures, is maintained. Therefore, no delay in the processing of information has been observed in the visual network with aging.

Age-related changes in the brain are also reflected in the oscillations of the brain, which can be measured using electroencephalography (EEG). The amplitude of components (peaks that are related to a particular process in the brain) in the processed signal, observed when many neurons fire together, is reduced in older individuals (Wlotko et al., 2010). There are two reasons why this reduction may occur: (1) neurons that fire together are geometrically less aligned and do no longer fire synchronously; (2) the latency of the component is more variable. Also, delays in the latency of the N400 component have been observed in older individuals. According to the global slowing hypothesis (Brinley, 1965), older adults are slower in every process, which should be reflected in the EEG data. Slower processing speed may, thus, be observed in older adults when carrying out a cognitive task, because they cannot focus on speed when they are focusing on responding as accurately as possible; known as the 'speed-accuracy tradeoff' (Ratcliff et al., 2007). Not being able to focus on both speed and accuracy is possibly related to a decrease in the strength of the tract between the pre-supplementary motor area and the striatum in older adults (Forstmann et al., 2011).

3.1.2 Effects of aging on the speech production process

Between 25% and 100% of the structural and functional changes in the brain are related to cognitive decline (Fjell and Walhovd, 2011). Cognitive decline caused by aging may have an effect on the speech production process. For example, older adults are less accurate in picture naming than younger adults (Connor et al., 2004). Decline in object naming is accompanied by a reduction of white and grey matter in the left temporal lobe (Cardenas et al., 2011). The temporal lobe has been associated with semantic memory, in which concepts are stored. When a concept activates a lemma (the word meaning) in the lexicon, semantically related lemmas get co-activated. The correct lemma is retrieved from the mental lexicon when lemmas that are semantically related to the target are sufficiently inhibited. Both, semantic memory and inhibition decline with aging (Harada et al., 2013).

After the lemma retrieval stage, the lexical word form, the lexeme, is retrieved. When there is insufficient information available about the lexeme, the phonological form of the word cannot be retrieved. The speaker experiences a temporal failure to produce a word, even though the word is well-known to him. This so-called tip-of-the-tongue phenomenon is observed more frequently in older adults, particularly in those with atrophy in the left insula (Shafto et al., 2007).

In the next stage of object naming, phonological encoding, the phonemes corresponding to the lexeme are retrieved and ordered and the phonological rules are applied. No aging effects have been reported for phonological encoding. Finally, the string of phonemes is phonetically encoded into an articulation plan. This plan specifies how the muscles of the mouth and throat will interact during the articulation of the word. Older individuals have a longer response duration for the production of both sequential and alternating syllable strings, which is associated with reduced cortical thickness in the right dorsal anterior insula and in the left superior temporal sulcus and gyrus (Tremblay and Deschamps, 2016).

sum, delayed lemma retrieval can be observed in older individuals (Cardenas et al., 2011) due to reduced semantic memory and poorer inhibition abilities (Harada et al., 2013). A delay at the lemma level may delay the onset of lexeme retrieval. Lexeme retrieval may be delayed due to tip-of-the-tongue states (Shafto et al., 2007). In this study, lemma and lexeme retrieval are studied in picture-naming tasks, while phonological and phonetic encoding are studied in nonword-production tasks. Since lemma and lexeme retrieval do not play a role in nonword-production tasks, delays in these stages cannot delay the onset of phonological and phonetic encoding. Aging is not expected to have an effect on these two stages, because no aging effects on phonological encoding have been reported. Also, the task used to study phonetic encoding is different from the task used by Tremblay and Deschamps (2016). An overview of the stages in spoken word and nonword production that may change in later adulthood is provided in Figure 3.1.

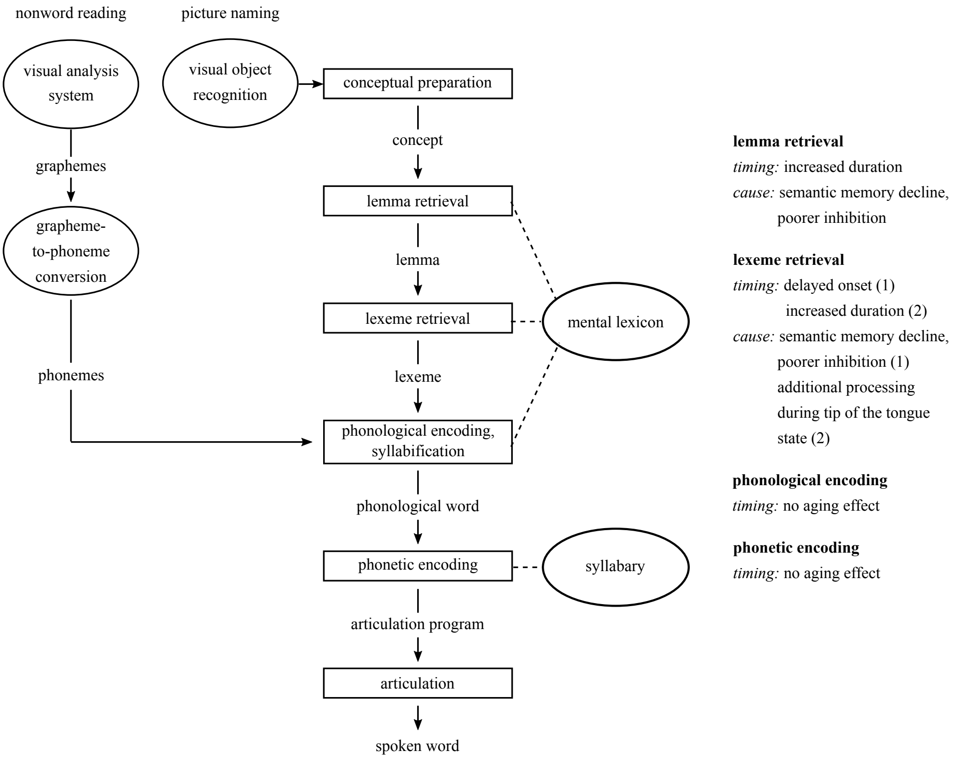


Figure 3.1: Stages in the model of spoken word and nonword production based on Levelt, Roelofs and Meyer (1999) and how they may change in later compared to earlier adulthood.

3.1.3 Current study

The hypothesis that the lemma and lexeme retrieval stage are delayed in older compared to younger individuals, whereas phonological and phonetic encoding are similar in both groups can be tested using EEG. Since each speech production stage has its own timing (Indefrey, 2011), it is possible to identify the individual stages using tasks in which more processing is required at the particular stage. Lemma retrieval requires more effort when the number of previously retrieved lemmas from neighboring nodes increases. This effect is referred to as the 'cumulative semantic interference effect' (Howard et al., 2006). Two EEG studies have used this effect to target the stage of lemma retrieval, which has been identified from 150 to 225 ms (Maess, et al., 2002) and from 200 to 380 ms after stimulus presentation (Costa et al., 2009).

Lexeme retrieval requires more effort when the age of acquisition (AoA) of words increases (Laganaro and Perret, 2011; Laganaro et al., 2012; Valente et al., 2014). This stage has been identified in a time window from 120 to 350 ms after stimulus presentation and around 280 and 150 ms before response onset (Laganaro and Perret, 2011), from 380 to 400 ms after stimulus presentation and up to 200 ms before response onset (Laganaro et al., 2012) and from 380 after stimulus presentation up to 100 ms before response onset (Valente et al., 2014).

Phonological encoding requires more effort when the number of phonemes increases. So far, word-length effects have not been identified in EEG studies, meaning that the time frame of phonological encoding has not been identified yet using this manipulation (Hendrix et al., 2017; Valente et al., 2014). However, other tasks, such as comparing overt and covert production of nouns and verbs, have been used to track phonological encoding (Sahin et al., 2010). In the current study nonword length is used, which may lead to different findings.

Syllable frequency is known to have an effect on phonetic encoding: when syllable frequency decreases, phonetic encoding requires more effort (Levelt and Wheeldon, 1994). In a task in which phonemes were inserted into nonwords with varying frequency in a nonword-reading task, the syllable frequency effect has been identified using EEG from 170 to 100 ms before response onset (Bürki et al., 2015). Our methodology is different, because participants were asked to read the nonwords, not to insert phonemes. It is, therefore, unclear what to expect.

Hence, for the current study, the cumulative semantic interference effect, the AoA-effect, the effect of nonword length in phonemes and the syllable frequency effect will be used to track the speech production stages in a group of younger adults and in a group of older adults. The time windows of the stages in both groups will be identified. If the time windows of the stages differ between the two groups, that does not mean that the processing mechanisms are different (Nieuwenhuis et al., 2011). Therefore, a direct comparison of both groups will be made in the time windows of the relevant stages that were identified in the younger adults and the older adults. Additionally, the scalp distributions of the stages will be compared between the two groups.

3.2 Methods

3.2.1 Participants

For the group of young adults, 20 young adulthood native speakers of Dutch (5 males) participated. The mean age of the participants was 21.8 years (age range: 17-28 years). Participants in the group of older adults were 20 late adulthood native speakers of Dutch (7 males). Their average age was 55.4 years (range 40-65). The young adult participants are referred to as 'younger adults' and the late adulthood participants are referred to as 'older adults'. The younger adults' data will be the basis of this study and their data will be compared to those of the older adults.

All participants were right-handed, measured using the short version of the Edinburgh handedness inventory (Oldfield, 1971). They reported no problems in hearing and their vision was normal or corrected to normal. Also, they reported no reading difficulties. All participants were financially compensated and gave informed consent. The study was approved by the *Ethics Committee of Humanities* of the University of Groningen.

3.2.2 Materials

Lemma retrieval

The materials used in the lemma retrieval task were black-and-white drawings. The pictures originated from the *Auditief Taalbegripsprogramma (ATP;* Bastiaanse, 2010) and the *Verb and Action Test (VAT;* see Bastiaanse et al., 2016) for individuals with aphasia. The order in which the depicted nouns were presented was manipulated for the cumulative semantic interference effect. The pictures were grouped in sets of five semantically-related neighbors (e.g. bed, couch, cradle, closet, chair) that fit into a particular category (e.g. furniture, clothes, insects). The five nouns within one category had the same number of syllables and the same stress pattern, and were controlled for logarithmic lemma frequency in Dutch (Baayen et al., 1995). The depicted nouns were all mono- or disyllabic in Dutch.

For the selection of final items, a picture-naming task was carried out by four participants (one male) with a mean age of 22 years, (age range: 21-23 years). Items that were named incorrectly by more than one participant were removed. The 125 selected items had an overall name agreement of 91.4%. The overall mean logarithmic lemma frequency was 1.28 (range: 0-2.91). The same set of pictures was used in two lists with reversed conditions to avoid an order of appearance effect. The lists were presented in three blocks of 30 items and one block of 35 items. The items are provided in Appendix 1.

The pictures were presented on a computer screen and participants were asked to name the pictures as quickly and accurately as possible. Before the picture was presented, a black fixation cross on a white background was shown for 500 ms. The function of the fixation cross was to draw attention and to announce that a picture was presented soon. The picture was shown for 5 seconds. Items within one category were not presented directly after another.

Lexeme retrieval

The pictures for this test originated from the same sources as the materials on the first test and represented mono- and disyllabic nouns in Dutch. Items were controlled for AoA (Brysbaert et al., 2014) and lexeme frequency (Baayen et al., 1995).

Four participants (one male) with a mean age of 20.7 years (age range 19-22) took part in a picture naming task for pretesting the materials. These participants had not taken part in the lemma retrieval task. Items that were named incorrectly by more than one participant were omitted.

The 140 selected items had an overall name agreement of 93.9%. AoA ranged from 4.01 years for the noun ‘book’ to 9.41 years for the noun ‘anchor’, with a mean of 5.96 years. The mean logarithmic lexeme frequency was 1.02 (range: 0-2.44). The correlation between AoA and lexeme frequency in the items is high ($r(138) = -.28$, $p < .001$). Therefore, in the analysis, only AoA has been taken into account. The items were organized in one list including four blocks of 35 items. The order of the items was randomized per block, so that every participant named the items in a different order. The items are provided in Appendix 2.

The procedure of the lexeme retrieval task was the same as the procedure of the lemma retrieval task. Since there was some item overlap between the lemma and lexeme retrieval tasks, the two tasks were never administered consecutively. A nonword task was always administered in between.

Phonological and phonetic encoding

To identify the stages of phonological and phonetic encoding, a nonword reading task was used.[10] All nonwords were disyllabic and composed of existing Dutch syllables. The combination of the two syllables resulted in a nonword, e.g. 'kikkels' or 'raalkro'. The nonwords were controlled for spoken syllable frequency (Nederlandse Taalunie, 2004). Two lists of nonwords were developed in written form for the reading task. The two lists contained the same syllables, but the syllables were combined differently, thus the nonwords were unique.

The nonwords were pretested in a reading task by four participants who took part in pretesting the picture naming tasks as well. Each list was pretested with two participants. The 140 selected items for List 1 had an accuracy rate of 100%; 8% of the nonwords in List 2 were produced incorrectly. The syllables used in these items were combined into new nonwords. These nonwords were pretested again with two other participants. Their accuracy was 100%.

For each nonword, the average spoken syllable frequency was computed over its two syllables. For List 1, the mean frequency was 1136 (range: 257-4514) and 1077 (range: 257-4676) for List 2. Also, the number of phonemes in the nonwords was controlled for, because the duration of phonological encoding may increase with the number of phonemes. For both lists, the number of phonemes in the nonwords ranged from 3 to 8. The average number of phonemes was 5.33 for List 1 and 5.29 for List 2. The items are provided in Appendix 3.

The nonwords were presented in white letters on a black background. The font type Trebuchet MS Regular, size 64 was used. The stimulus was presented for 5 seconds and preceded by a fixation cross which was presented for 500 ms. Participants read either List 1 or List 2. Each list was divided into four blocks of 35 items. The order in which the nonwords were presented was randomized per block, so none of the participants read the nonwords in the same order. The instruction was to read the nonwords aloud as quickly and accurately as possible.

General procedure

During the experiments, participants were seated approximately 70 cm from the screen. E-Prime (E-Prime 2.0, 2012) was used to present the stimuli and to record the response times

[10] In fact, two nonword tasks were administered: reading and repetition. Since reading is more closely related to object naming (a visually presented stimulus evoking a spoken output), the data of the repetition task will be ignored.

and the responses. A voice key was used to detect the response times. The responses were recorded using a microphone that was attached to a headset. Before the experiment started, participants practiced the task with five items for the picture-naming tasks and with eight items for the nonword-reading task. Participants had the opportunity to take a short break between the four blocks of the experiments.

EEG data recording

EEG data were recorded with 128 (older adults) and 64 (younger adults) Ag/AgCl scalp electrodes (WaveGuard) cap using the EEGO and ASA-lab system (ANT Neuro Inc., Enschede, The Netherlands). These systems are entirely compatible; EEGO is the latest version. For the older adults only the 64 channels that were recorded in the younger group were analyzed. The full set of 128 electrodes was used in a different study. The electrode sites were distributed over the scalp according to the 10-10 system (Jasper, 1958) for the system with 64 electrodes and according to the 10-5 system for the system with 128 electrodes. Bipolar electrodes were used to record vertical ocular movements, such as eye blinks, for which the electrode sites were vertically aligned with the pupil and located above and below the left eye. Impedance of the skin was kept below 20 kΩ, which was checked before every experiment. Data were acquired with a sampling rate of 512 Hz and reference was recorded from the mastoids.

3.2.3 Data processing and analysis

Behavioral data

The audio recordings of the participants' responses were used to determine the speech onset time. The speech onset time in each audio file was manually determined using the waveform and the spectrogram in Praat (Boersma and Weenink, 2018). The speech onset times based on the audio files were used as response events in the response-locked EEG analysis. R was used for the statistical analysis of the behavioral and item data (R Core Team, 2017).

Trials to which participants responded incorrectly were excluded from the analysis (lemma retrieval: 7.8%; lexeme retrieval: 7.3%; phonological and phonetic encoding: 1.9%). Also, responses that included hesitations or self-corrections qualified as errors (lemma retrieval: 2.6%; lexeme retrieval: 2.6%; phonological and phonetic encoding: 0.8%). Items to which many participants responded extraordinarily fast or slow were excluded from the EEG analysis (lemma retrieval: 8%; lexeme retrieval: 18.6%; phonological and phonetic encoding: 12.1%). The average response time was computed over all accepted trials. Trials exceeding this average by 1.4 standard deviations were disregarded.

EEG data

The EEG data were preprocessed using EEGLAB (Delorme and Makeig, 2004) as an extension to MATLAB (The MathWorks, 2015a). After re-referencing to the average reference of the mastoids, the data were filtered with a 50 Hz notch filter to remove electricity noise and band-pass filtered from 0.2 to 30 Hz. Then, the data were resampled to 128 Hz. Independent components analysis on all channels was used for artifact detection. Artifact components, such as eye blinks, were removed through visual inspection. Also, the effect of component removal on the data was visually inspected. The continuous data were segmented per trial from 200 ms until 2 seconds after stimulus onset. A baseline correction was applied over the data epochs, using the 200 ms before stimulus onset as a baseline. Then, the events of disregarded trials were removed. To study the time window from the stimulus onset until the response onset, both stimulus-locked analyses, in which the time window after stimulus onset is analyzed, and response-locked analyses, in which the backwards time window before the response onset is analyzed, were carried out. For the stimulus-locked analysis, the data epochs were segmented from stimulus onset until one sampling point (8 ms) after the earliest response time. This one extra sampling point was removed before the analysis. The start of the response-locked analysis was determined by subtracting the stimulus-locked time window from the response onset. Depending on the task, accepted trials were coded into two or three conditions for the statistical analysis. The conditions are specified below per experiment. These data were exported from EEGLAB into the format used in FieldTrip (Oostenveld et al., 2011), which was used for the statistical analysis. Finally, the structure of the data files was prepared for a cluster-based permutation analysis (Maris and Oostenveld, 2007).

The aims of the analyses were to identify the time window of lemma retrieval with the cumulative semantic interference effect, the time window of lexeme retrieval with the AoA-effect, the time window of phonological encoding with the nonword length in phonemes effect and the time window of phonetic encoding with the syllable frequency effect. These time windows were identified in the group of older adults and in the group of younger adults using group-level cluster-based permutation analyses carried out over all participants per group. The cumulative semantic interference effect was computed as the difference between the first and the fifth presented item within a category. The difference between words with an AoA of around 5 years and words with an AoA of around 6 years, as well as the difference between words with an AoA of 5 years and words with an AoA of around 7 years were used to compute the AoA-effect. The effect of nonword length in phonemes was computed as the difference between nonwords consisting of 4 phonemes and nonwords consisting of 5 phonemes, as well as the difference between nonwords consisting of 4 phonemes and nonwords consisting of 6 phonemes. The difference between nonwords with a high syllable frequency of 1000-1500 and nonwords with a moderate syllable frequency of 500-1000, as well as the difference between nonwords with a high syllable frequency of 1000-1500 and nonwords with a low syllable frequency of 250-500 were used to compute the syllable frequency effect. In every analysis, the number of permutations computed was 5000. The Monte Carlo method was used to compute significance probability, using a 2-sided dependent samples T-test. A family-wise error rate with an α of 0.025 was used to correct for the multiple comparison problem. In the first analysis of every experiment, the entire time window from stimulus onset until 100 ms before response onset was tested. When an effect was revealed in this large time window, a smaller time window around the effect was tested once, so a more specific timing of the effect could be reported. An effect was defined as a cluster of at least 5 neighboring electrodes that was observed in one or more consecutive sampling points. The smaller time window was tested on all sampling points of the effect. Finally, the time windows of the stages in older and younger adults were compared. This method cannot show whether the two groups differ (Nieuwenhuis et al., 2011). Therefore, the EEG data of both groups have been compared in the time windows of the stages for every single condition using a cluster-based permutation analysis. Again, the Monte Carlo method was used to compute significance probability, but now a 2-sided independent samples t-test ($\alpha = 0.025$) was used to compare the two subject groups.

Additionally, a z-score mapping analysis (Thatcher et al., 2002) was carried out to compare the scalp distributions of the older adults to those of the younger adults during the speech production stages. For each experiment, the data were analyzed in relevant time windows and conditions for which significant clusters were found in the cluster-based permutation analysis of the older and the younger adults. The length of these time windows varied between the participant groups, which would have caused a difference in the number of time points included in the analysis. To avoid this difference, the number of time points centered around the median of the longest time window used in the analysis was made equal to the number of time points in the shortest time window. For each time point, z-scores were computed per electrode. The mean computed over the younger adults' data was subtracted from each data point from the older adults' data individually. This subtraction was divided by the standard deviation computed over the younger adults' data. Mean z-scores were computed per condition. When the mean z-score deviated more than one standard deviation from zero, the difference between the age groups qualified as significant.

3.3 Results

The mean, standard deviation and range of the response time data from the three experiments are provided per participant group in Table 3.1. For all analyses on response time, only the correct responses were used.

Table 3.1: Response times after stimulus presentation in ms of the younger and older adults on all tasks. Means (M), standard deviations (SD) and ranges (RNG) are reported as M (SD, RNG).

Task	young	old
Picture naming: lemma retrieval	932 (*216*, 602-1461)	944 (*213*, 603-1460)
Picture naming: lexeme retrieval	938 (*199*, 626-1440)	946 (*201*, 628-1439)
Nonword reading: phonological and phonetic encoding	690 (*116*, 502-966)	699 (*119*, 504-965)

3.3.1 Behavioral results

Younger adults

At all tasks, the younger adults performed at ceiling. The percentages of correct responses were 92.4% for lemma retrieval, 92.9% for lexeme retrieval and 98% for the nonword-reading task targeting phonological and phonetic encoding. On the *lemma retrieval* task, a cumulative semantic interference effect was found on the response time ($F(1,765)=13.38$, $p < 0.001$). Increased response times were found for pictures within a category that were presented at the fifth ordinal position compared to pictures that were presented at the first ordinal position. An AoA-effect on the response time was identified on the *lexeme retrieval* task ($F(1,2205)=104.01$, $p < 0.001$). Response time increased as AoA advanced. Nonword length in number of phonemes is relevant at the level of *phonological encoding* and turned out to be a significant factor: response times increased when nonwords consisted of more phonemes ($F(1,2096)=5.71$, $p = 0.017$). The frequency of the syllables was varied to tap into *phonetic encoding*. Response times were found to decrease when syllable frequency increased ($F(1,2320)=6.35$, $p = 0.01$).

Older adults

Like the younger adults, the older adults performed at ceiling on all tasks. The percentages of correct responses were 86.8% for lemma retrieval, 87.6% for lexeme retrieval, and 96.5% for the nonword-reading tasks. A cumulative semantic interference effect was found on the *lemma retrieval* task ($F(1,721)=7.60$, $p = 0.006$). Increased response times were found for pictures within a category that were presented at the fifth ordinal position compared to those presented at the first ordinal position. Also, increased response times were found for items with a later AoA on the task targeting *lexeme retrieval* ($F(1,2061)=43.38$, $p < 0.001$). In the nonword-reading task, response times increased with the nonword length in number of phonemes, which was used as a marker for *phonological encoding* ($F(1,1943)=5.60$, $p = 0.018$). Furthermore, to target *phonetic encoding*, a decrease in syllable frequency of the nonwords was found to increase response times ($F(1,2146)=11.68$, $p < 0.001$).

Differences between younger and older adults

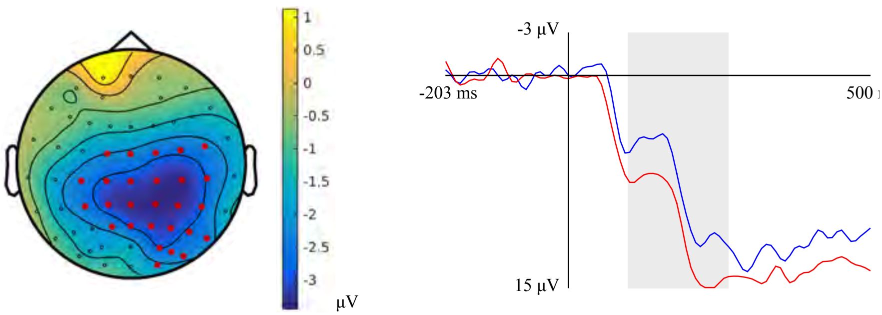
On *all* tasks, differences in response times between both age groups were found. The older adults responded slower than the younger adults on the *lemma retrieval* task ($F(1, 1488) = 4.81$, $p = .028$), the *lexeme retrieval* task ($F(1, 4268) = 7.14$, $p = .007$) and the nonword-reading task targeting *phonological* and *phonetic encoding* ($F(1, 4468) = 28.58$, $p < .001$). Moreover, an interaction effect of AoA and participant age was found ($F(1, 4268) =4.51$, $p = 0.034$). The group of older adults showed a smaller AoA-effect ($F(1, 2061) =43.38$, $p < 0.001$) than the group of younger adults ($F(1, 2205) =104.01$, $p < 0.001$).

3.3.2 EEG results

For the presentation of the EEG results, we will first present the results of the cluster-based permutation analysis for each task in the younger adults and then in the older adults to identify the time windows of the effects in these groups. Then the differences between the two groups in these time windows computed with cluster-based permutation analyses will be presented along with the comparisons of the scalp distributions of both age groups. The EEG statistics are given in Appendix 4 (younger adults), Appendix 5 (older adults) and Appendix 6 (comparison of older and younger adults).

Younger adults

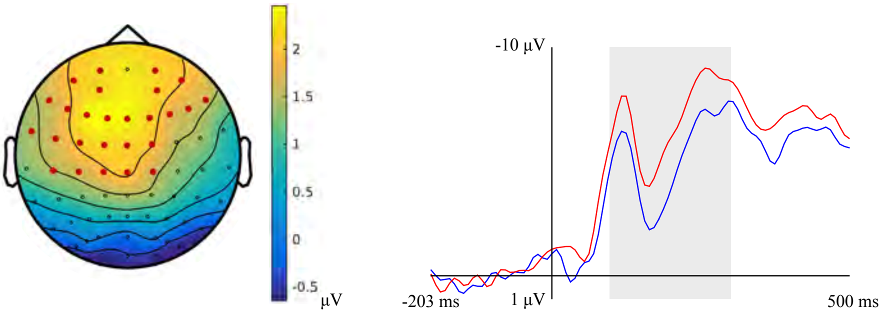
In the younger adults, a difference between the first and fifth ordinal position that was taken as evidence for the stage of *lemma retrieval* was revealed in the latency range from 100 to 265 ms ($p = .005$) after stimulus onset. The difference was most pronounced over right central and posterior sensors. In the response-locked analysis, an effect was found from 445 to 195 ms ($p = .004$) before response onset. The effect was most pronounced over central and posterior sensors bilaterally and over the right frontal electrodes. The scalp distribution of the stimulus-locked effect and the waveforms of the grand averages for the first and fifth ordinal position are shown in Figure 3.2.



Difference	1st item vs 5th item in ordinal position	grand averages for PO6
Timing	100 - 265 ms post-stimulus onset	1st item in ordinal position = blue 5th item in ordinal position = red

Figure 3.2: Left: the cluster related to the cumulative semantic-interference effect in the younger adults that was revealed in the stimulus-locked analysis of the lemma retrieval task. Electrodes included in the cluster are marked in red. Right: the waveforms of the grand averages for the 1st (in blue) and 5th item in ordinal position (in red) for electrode PO6 in the younger adults.

Testing for an AoA-effect targeting *lexeme retrieval* in the latency range from 100 to 300 ms after stimulus onset in the younger adults, the cluster-based permutation test revealed a difference between the items with an early AoA and items with a moderate AoA ($p = .002$). The difference was most pronounced on bilateral frontal and central sensors, as shown in Figure 3.3. Figure 3.3 also shows the waveforms of the grand averages for the early and moderate AoA conditions. In the response locked cluster-based permutation analysis, a difference between items with an early AoA and items with a late AoA was revealed from 475 to 330 ms before response onset. The response-locked AoA-effect was most pronounced on bilateral frontal and bilateral central electrodes ($p < .001$).



Difference	AoA of ca. 5 vs ca. 6 years
Timing	100 - 300 ms post-stimulus onset

grand averages for F1
AoA of ca. 5 years = blue
AoA of ca. 6 years = red

Figure 3.3: Left: the cluster related to the AoA-effect in the younger adults that was revealed in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for an AoA of ca. 5 (in blue) and 6 years (in red) for electrode F1 in the younger adults.

A stimulus-locked length effect was revealed from 350 to 415 ms for the comparison of nonwords consisting of 4 and 5 phonemes ($p = .0032$) targeting *phonological encoding*, which is shown in Figure 3.4. The waveforms of the grand averages for nonword length in 4 and 5 phonemes are provided in Figure 3.4 as well. Also, a stimulus-locked length effect was revealed as a difference between nonwords consisting of 4 and 6 phonemes in a time window from 390 to 425 ms after stimulus presentation ($p = .0046$). Both stimulus-locked effects were most pronounced over the bilateral centro-posterior electrodes. In the response-locked analysis, a length effect was identified as a difference between 4 and 5 phonemes from 335 to 320 ms before response onset, which was most pronounced over bilateral central and left posterior electrodes ($p = .0084$). Also, a length effect for the difference between 4 and 6 phonemes was revealed from 330 to 320 ms before response onset (p= .0084). This effect was most pronounced in right central and bilateral posterior electrodes.

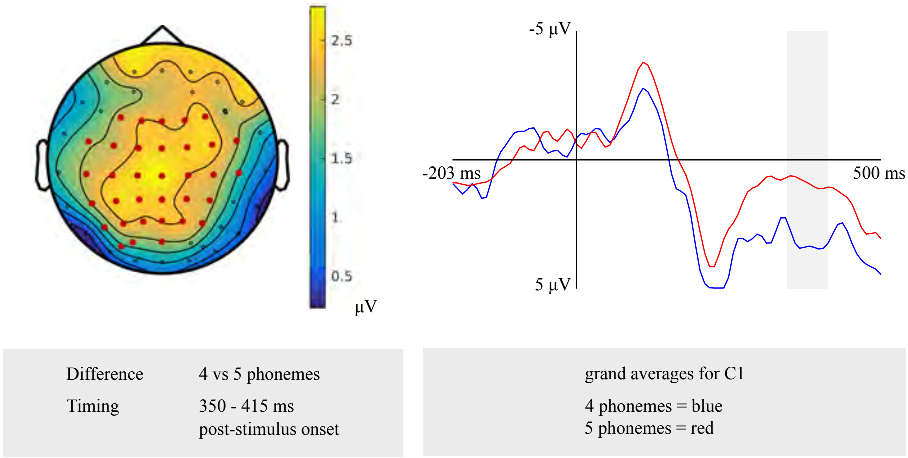


Figure 3.4: Left: the cluster related to the effect of nonword length in the younger adults that was revealed in the stimulus-locked analysis of the task targeting phonological encoding. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for a nonword length of 4 (in blue) and 5 phonemes (in red) for electrode C1 in the younger adults.

Testing for a syllable frequency effect targeting *phonetic encoding* in the latency range from 400 to 450 ms after stimulus onset in the younger adults, the cluster-based permutation test revealed a difference between items with a high syllable frequency and items with a moderate syllable frequency (p = .020). In this latency range, the difference was most pronounced over the central sensors bilaterally. Another stimulus-locked syllable frequency effect was found as a difference between items with a high syllable frequency and items with a low syllable frequency in a time window from 350 to 450 ms after stimulus onset (p = .012), which is shown in Figure 3.5. The difference was most pronounced at the frontal and central sensors bilaterally. In Figure 3.5 the waveforms of the grand averages for the high and low syllable frequency items are provided as well. In the response-locked analysis, a difference between items with a high syllable frequency and items with a low syllable frequency was revealed in a time window from 250 to 200 ms before response onset (p = .021). The effect was most pronounced at bilateral central sensors.

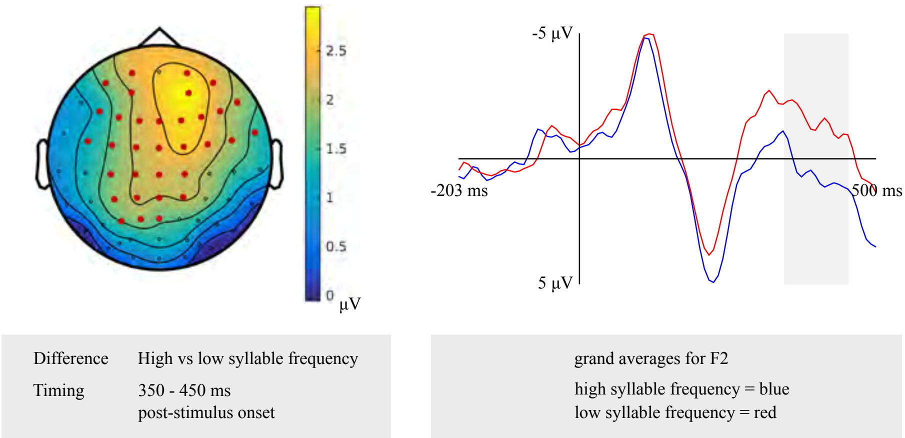


Figure 3.5: Left: the cluster related to the syllable frequency effect in the younger adults that was revealed in the stimulus-locked analysis of the task targeting phonetic encoding. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for high (in blue) and low syllable frequency (in red) for electrode F2 in the younger adults.

Older adults

3

In the older adults, testing for a cumulative semantic interference effect in the latency range from 540 to 450 ms before response onset, the cluster-based permutation test revealed a difference between the first and fifth ordinal position ($p = .006$) that was taken as evidence for the stage of *lemma retrieval*. The difference was most pronounced over left posterior electrodes during the first 60 ms and most pronounced over the right posterior electrodes during the last 50 ms of the effect. No effect was found in the stimulus-locked analysis. The scalp distribution and the waveforms of the first and fifth ordinal position's grand average are shown in Figure 3.6.

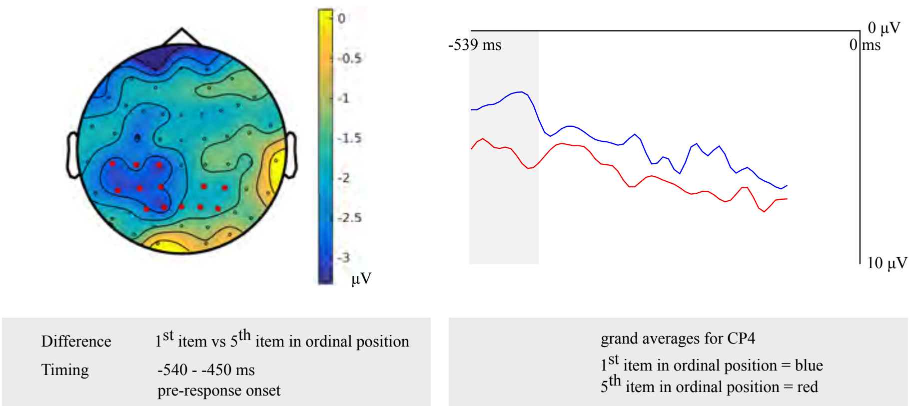
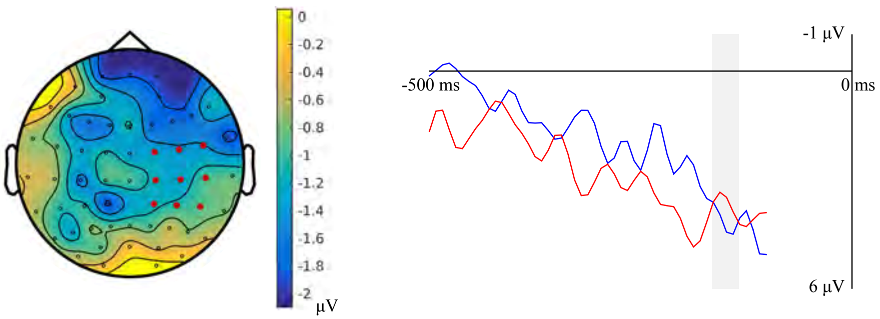


Figure 3.6: Left: the cluster related to the cumulative semantic-interference effect in the older adults that was revealed in the response-locked analysis of the lemma retrieval task. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for the 1st (in blue) and 5th item in ordinal position (in red) for electrode CP4 in the older adults.

For *lexeme retrieval*, an AoA-effect was revealed in the cluster-based permutation analysis in three response-locked time windows as a difference between items with an early AoA (of around 5 years) and items with a moderate AoA (of around 6 years). The AoA-effect was most pronounced over centro-posterior electrodes in the earliest cluster from 430 to 420 ms (p = .012) before response onset. In the second cluster, from 210 to 195 ms (p = .009) before response onset, the effect was most evident over the right frontal electrodes. The AoA-effect was most distinct over right central electrodes in the last cluster with the longest duration from 165 to 140 ms (p= .013) before response onset, which is depicted in Figure 3.7. In Figure 3.7, the waveforms of the grand averages for the early and moderate AoA items are provided as well. No differences were found between items with an early AoA and items with a late AoA (of around 7 years). Also, no AoA-effect was found in the stimulus-locked analysis.



Difference	AoA of ca. 5 vs ca. 6 years
Timing	-165 - -140 ms pre-response onset

grand averages for FC2
AoA of ca. 5 years = blue
AoA of ca. 6 years = red

Figure 3.7: Left: the cluster related to the AoA-effect in the older adults that was revealed in the response-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for an AoA of ca. 5 (in blue) and 6 years (in red) for electrode FC2 in the older adults.

For *phonological encoding*, the effect of the length in the number of phonemes on nonword reading was used in the cluster-based permutation analysis. In the older adults, a length effect was revealed as a difference between nonwords with a length of 4 and 6 phonemes in the time windows from 100 to 135 ms (p = .019) and from 280 to 300 ms (p = .0038) after stimulus onset. In the first time-window, the length effect was most pronounced over the right posterior electrodes, as shown in Figure 3.8. The waveforms of the grand averages for items consisting of 4 and 6 phonemes are provided in Figure 3.8 as well. The effect was most pronounced over bilateral frontal and central electrodes in the second time window. No effects were found for the comparison of nonwords with a length of 4 and 5 phonemes. Also, no length effects were found in the response-locked analysis.

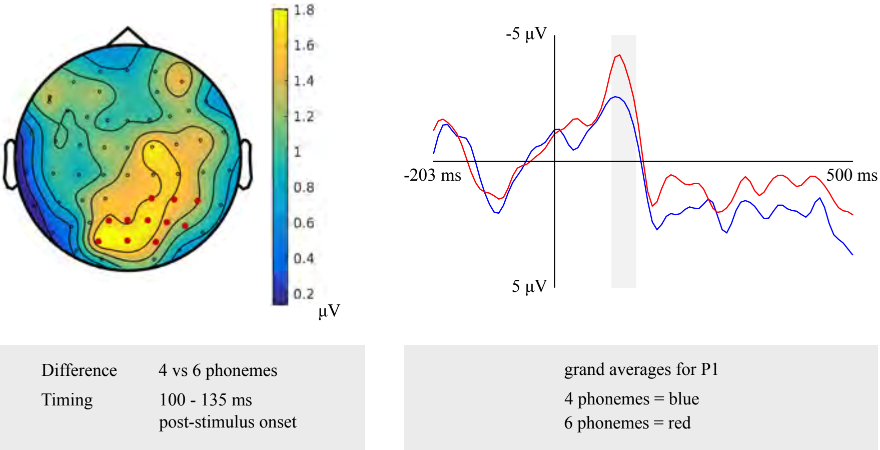


Figure 3.8: Left: the cluster related to the effect of nonword length in phonemes in the older adults that was revealed in the stimulus-locked analysis of the task targeting phonological encoding. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for a nonword length of 4 (in blue) and 6 phonemes (in red) for electrode P1 in the older adults.

For tapping into *phonetic encoding*, the effect of syllable frequency on the nonword-reading task was used. The stimulus-locked cluster-based permutation analysis revealed a syllable frequency effect for reading nonwords with a high syllable frequency (ranging from 1000 to 1500) as compared to reading nonwords with a moderate syllable frequency (ranging from 500 to 1000) in a time window from 280 to 300 ms (p = .0094) and in a time window from 365 to 375 ms (p = .022) after stimulus presentation. The earliest effect was most pronounced over electrodes covering the right hemisphere, the later effect over the posterior electrodes. Furthermore, the comparison of nonwords with a high syllable frequency to nonwords with a low syllable frequency (ranging from 250 to 500) revealed effects from 280 to 290 ms (p = .0196) and from 420 to 455 ms (p = .0078) after stimulus onset. The effect starting at 280 ms was most pronounced over right-posterior electrodes, while the later effect shown in Figure 3.9 was most pronounced over bilateral posterior electrodes. The waveforms of the high and low frequency items' grand averages are shown in Figure 3.9 as well. Also, the syllable frequency effect was revealed from 455 to 435 ms (p = .016) before response onset. This effect was most pronounced over bilateral frontal and central electrodes.

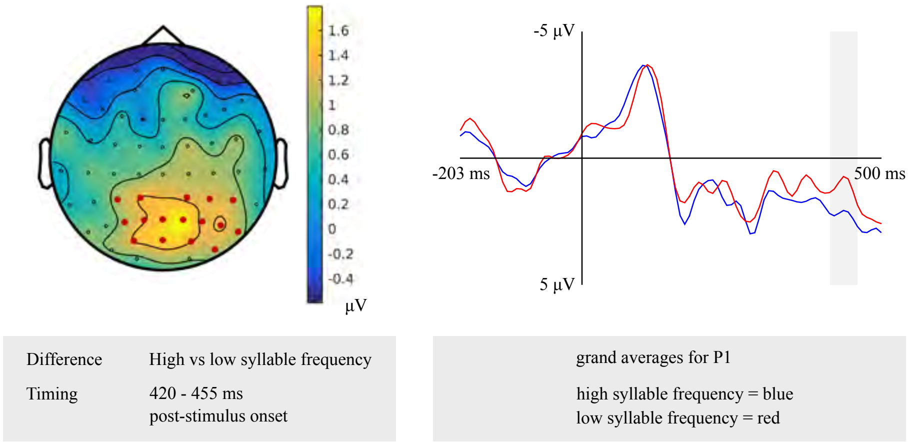


Figure 3.9: Left: the cluster related to the syllable frequency effect in the older adults that was revealed in the stimulus-locked analysis of the task targeting phonetic encoding. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for a high (in blue) and low syllable frequency (in red) for electrode P1 in the older adults.

Differences between younger and older adults

Comparing the older and younger adults in the time window for *lemma retrieval* in younger adults from 100 to 265 ms after stimulus presentation in the fifth ordinal position, the cluster-based permutation analysis showed that both groups differed. In this time window, two effects were identified: a positive (p = .0026) and a negative one (p = .0022). The electrodes over which the positive effect was most pronounced were located in frontal regions bilaterally. The negative effect was most pronounced in bilateral posterior regions. Also, in the time window for lemma retrieval in older adults from 540 to 450 ms before response onset, both groups were found to differ. Differences were observed as a positive (p = .023) effect that was most pronounced over bilateral frontal electrodes and a negative effect (p = .013) that was most pronounced over bilateral posterior electrodes. Furthermore, a difference between the groups was observed in the response-locked time window for lemma retrieval in the younger adults from 445 to 195 ms before response onset (p = .0044). This difference was most pronounced in the posterior regions bilaterally. The clusters are shown in Figure 3.10a along with the waveforms of the grand averages for younger and older adults.

Based on the results from the cluster-based permutation analysis, a time window from 540 to 450 ms before response onset in older adults was compared to a time window from 365 to 275 ms before response onset in young adults. The z-scores computed for the first (M = 0.03, SD = 0.15, range = -0.37 – 0.27) and the fifth ordinal position (M = -0.12; SD = 0.15, range = -0.41 – 0.19) indicated no differences in scalp distributions between the older and the younger adults. Figure 3.10b shows the z-scores of the individual electrodes mapped onto the scalp distribution per ordinal position.

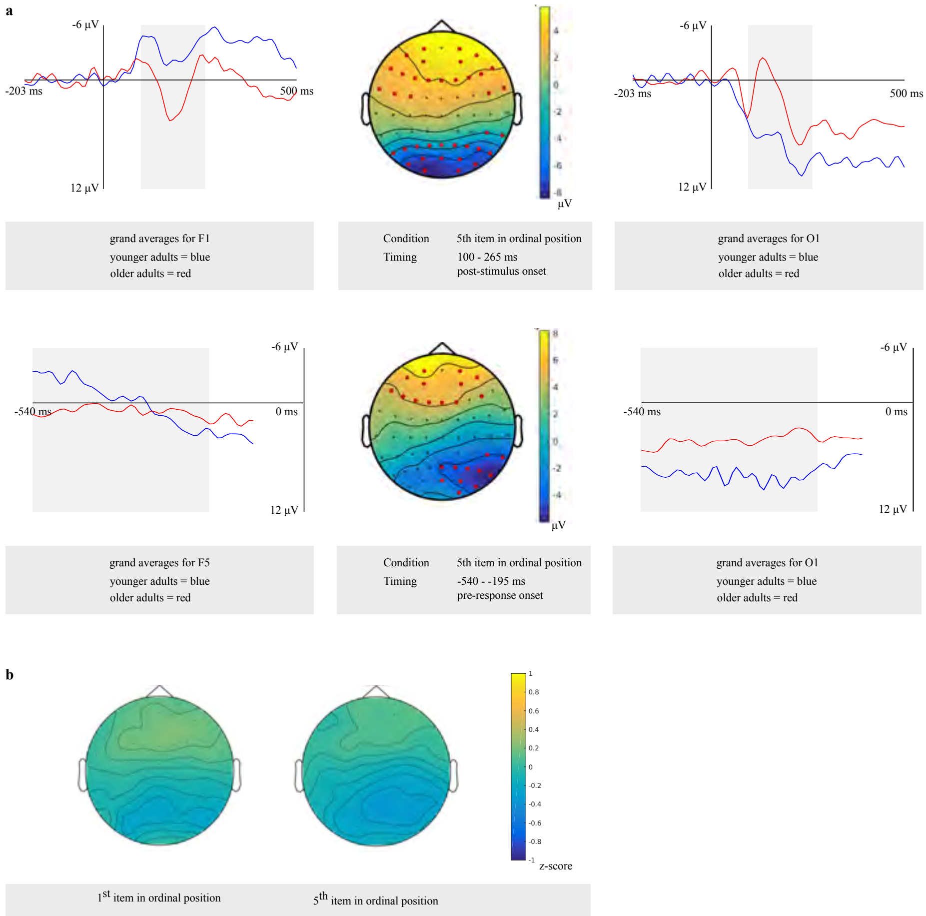


Figure 3.10a: Difference between younger and older adults identified in the stimulus-locked (top) and response-locked analysis (bottom) for the 5th item in ordinal position in the lemma retrieval task, showing a positive cluster over frontal electrode sites and a negative cluster over posterior electrode sites. Electrodes included in the clusters are marked in red. Waveforms of the grand averages for the younger (in blue) and older adults (in red) of the frontal electrodes F1 (top left) and F5 (bottom left) and posterior electrodes O1 (right).

Figure 3.10b: Scalp distributions per ordinal position showing the z-scores of the older adults compared to the younger adults.

In the time window for *lexeme retrieval* identified for the younger adults, from 100 to 300 ms after stimulus presentation, a difference between the older and younger adults was found for items with a moderate AoA ($p = .0022$). The difference was most pronounced in frontocentral regions bilaterally, as shown in Figure 3.11a. Also, the waveforms of the younger and older adults' grand averages are provided in Figure 3.11a. The response-locked time windows for lexeme retrieval from 430 and 140 ms before response onset identified in the older adults and from 475 to 330 ms before response onset identified in the younger adults did not reveal any differences between the groups.

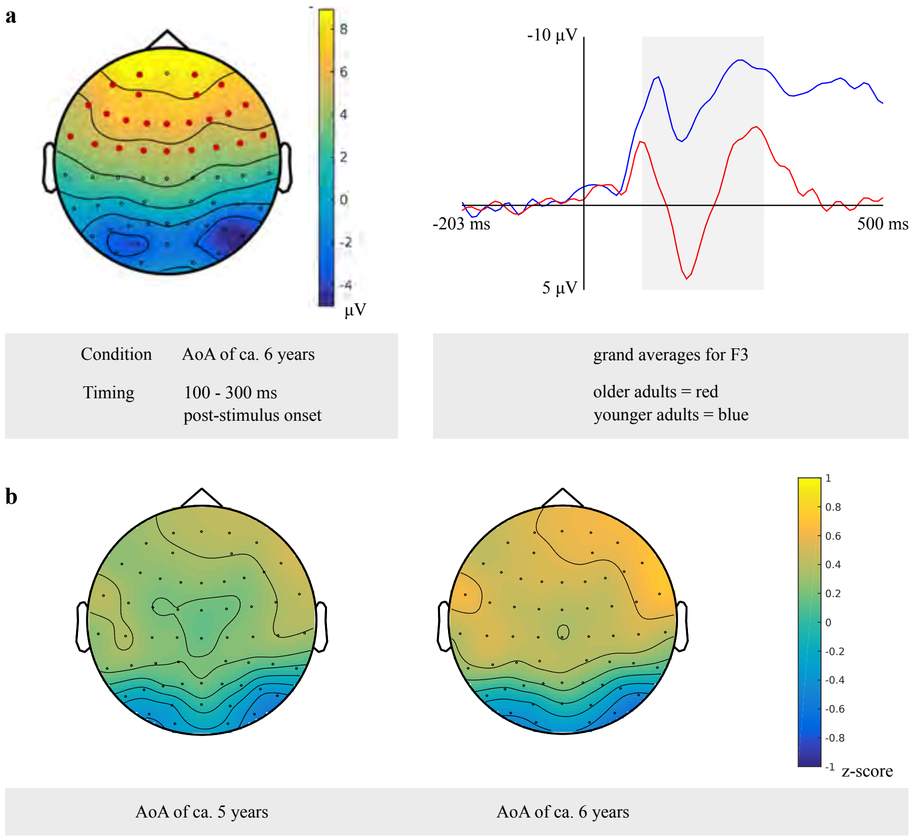


Figure 3.11a: Left: cluster related to the difference between younger and older adults identified in the stimulus-locked analysis for an AoA of ca. 6 years in the lexeme retrieval task. Electrodes included in the cluster are marked in red. Right: waveforms of the grand averages for the younger (in blue) and older adults (in red) of the electrodes F3.

Figure 3.11b: Scalp distributions per AoA showing the z-scores of the older adults compared to the younger adults.

The cluster-based permutation analysis targeting *lexeme retrieval* revealed no difference between early and late AoA conditions in the older adults, thus the scalp distributions of the age groups could not be compared on these conditions. The age groups were compared on the early AoA and the moderate AoA conditions. A time window from 175 to 225 ms after stimulus presentation in the younger adults was compared to a time windows from 430 to 420 ms, from 210 to 195 ms and from 165 to 140 ms before response onset in the older adults. Based on the z-scores of the electrodes, no differences in scalp distributions were found between the older and the younger adults for the early AoA (M = 0.15, SD = 0.26, range = -0.64 – 0.64) and the moderate AoA conditions (M = 0.29, SD = 0.33, range = -0.64 – 0.89). This is shown in Figure 3.11b.

The cluster-based permutation analysis for *phonological encoding* showed differences between older and younger adults for nonwords consisting of 5 phonemes in a time window from 350 to 415 ms after stimulus presentation (p= .015). Also, for the nonwords consisting of 6 phonemes, a difference between both age groups was found from 390 to 425 ms after stimulus presentation (p =.014). Both time windows were identified for phonological encoding in the young adults. The differences were most pronounced in bilateral posterior regions, as shown in Figure 3.12a. Figure 3.12a also shows the waveforms of the grand averages of the younger and the older adults. In the time windows identified for the older adults, no differences between the groups were found. This result was also the case for the response-locked time windows identified for phonological encoding in the younger adults.

For the older adults, no difference was found between nonwords composed of 4 and 5 phonemes in the cluster-based analysis targeting *phonological encoding*, so the age groups cannot be compared on these conditions. The conditions with 4 and 6 phonemes were included in the scalp distributions analysis. Time windows from 390 to 425 ms after stimulus presentation and from 330 to 320 ms before response onset in the younger adults were compared to time windows from 105 to 135 ms and from 280 to 295 ms after stimulus presentation in the older adults. The z-scores revealed no differences in scalp distributions between the older and the younger adults for the 4 phonemes condition (M = -0.24, SD = 0.20, range = -0.74 – 0.12) and the 6 phonemes condition (M = -0.21, SD = 0.20, range = -0.74 – 0.11). The scalp distributions are shown in Figure 3.12b.

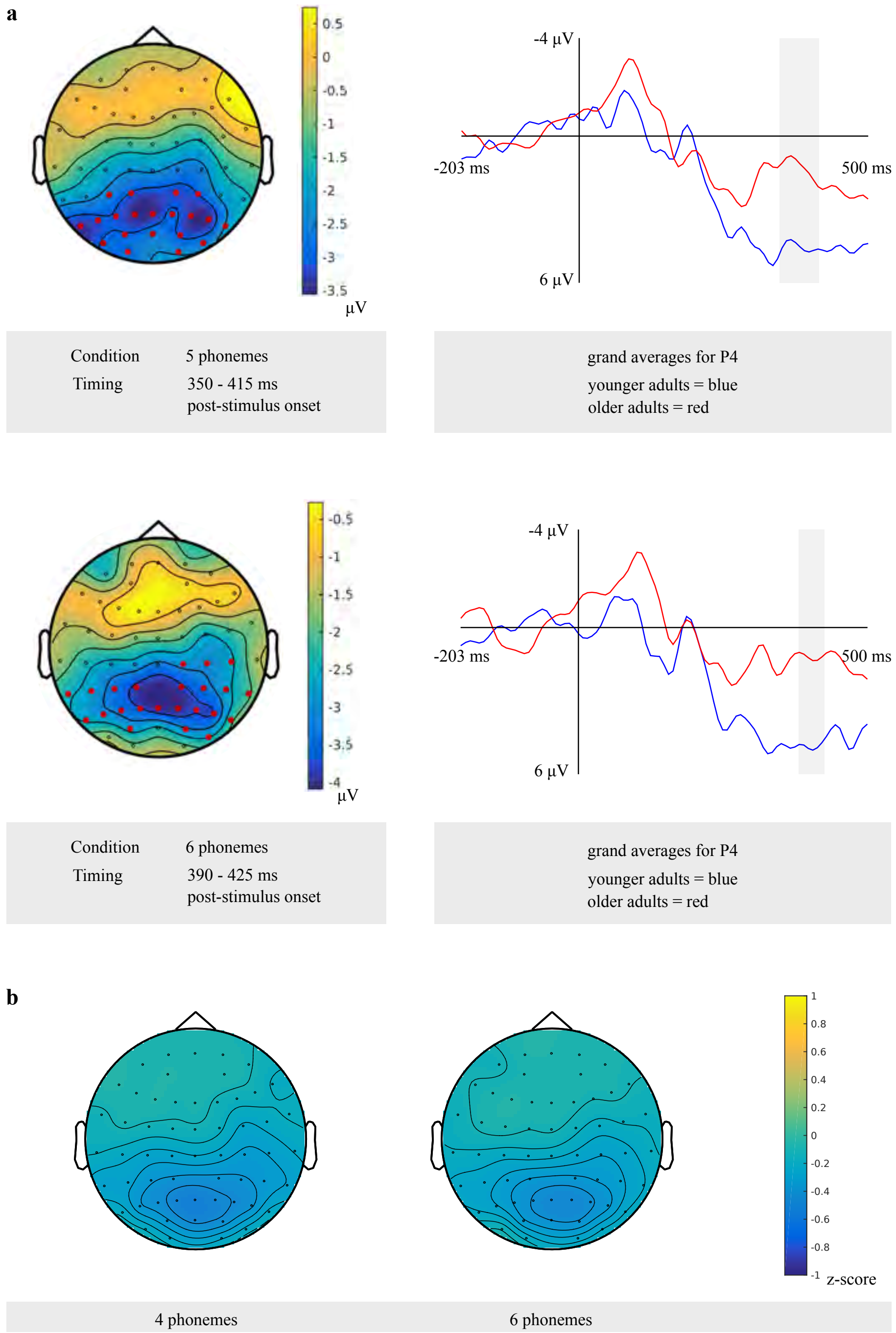

a
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
µV
-4 µV
-203 ms
500 ms
6 µV
Condition 5 phonemes
Timing 350 - 415 ms
post-stimulus onset
grand averages for P4
younger adults = blue
older adults = red
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
µV
-4 µV
-203 ms
500 ms
6 µV
Condition 6 phonemes
Timing 390 - 425 ms
post-stimulus onset
grand averages for P4
younger adults = blue
older adults = red
b
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
z-score
4 phonemes
6 phonemes

Figure 3.12a: Left: clusters related to the difference between younger and older adults identified in the stimulus-locked analysis for a nonword length of 5 (top) and 6 (bottom) phonemes in the task targeting phonological encoding. Electrodes included in the clusters are marked in red. Right: waveforms of the grand averages for the younger (in blue) and older adults (in red) for the electrodes P4.

Figure 3.12b: Scalp distributions per nonword length in phonemes showing the z-scores of the older adults compared to the younger adults.

For *phonetic encoding*, the cluster-based permutation analyses showed a difference between the older and the younger adults for moderate frequency nonwords from 280 to 375 ms after stimulus presentation (p = .007). This range corresponds to the time window identified for phonetic encoding in the older adults. The groups did not differ in the time window for the younger adults. For low frequency nonwords, a difference between both groups was found from 280 to 455 ms after stimulus presentation (p = .011). This time window corresponds to the time window identified for phonetic encoding in older adults, and also includes the time window in which phonetic encoding was identified in younger adults. Both effects were most pronounced in bilateral posterior regions, as shown in Figure 3.13a. This Figure also shows the waveforms of the grand averages for the younger and older adults. No differences between the groups were found in the response-locked time windows.

For nonwords with a high syllable frequency and a moderate syllable frequency, a time window from 410 to 440 ms after stimulus presentation in younger adults was compared to time windows from 280 to 300 ms and from 365 to 375 ms after stimulus presentation in older adults. Based on the z-scores, no differences in scalp distributions were found between the older and the younger adults for both high frequency (M = -0.15, SD = 0.11, range = -0.33 – 0.10) and moderate frequency conditions (M = -0.11, SD = 0.11, range = -0.36 – 0.12). Also, z-scores for nonwords with a high syllable frequency and a low syllable frequency were computed to compare a time window from 385 to 440 ms after stimulus presentation in younger adults to time windows from 280 to 290 ms and from 420 to 455 ms after stimulus presentation and from 450 to 460 ms before response onset in older adults. For the high frequency (M = -0.15, SD = 0.12, range = -0.36 – 0.18) and the low frequency conditions (M = -0.11, SD = 0.14, range = -0.44 – 0.17), no differences in scalp distributions based on the z-scores were found between older and younger adults. The scalp distributions are shown in Figure 3.13b.

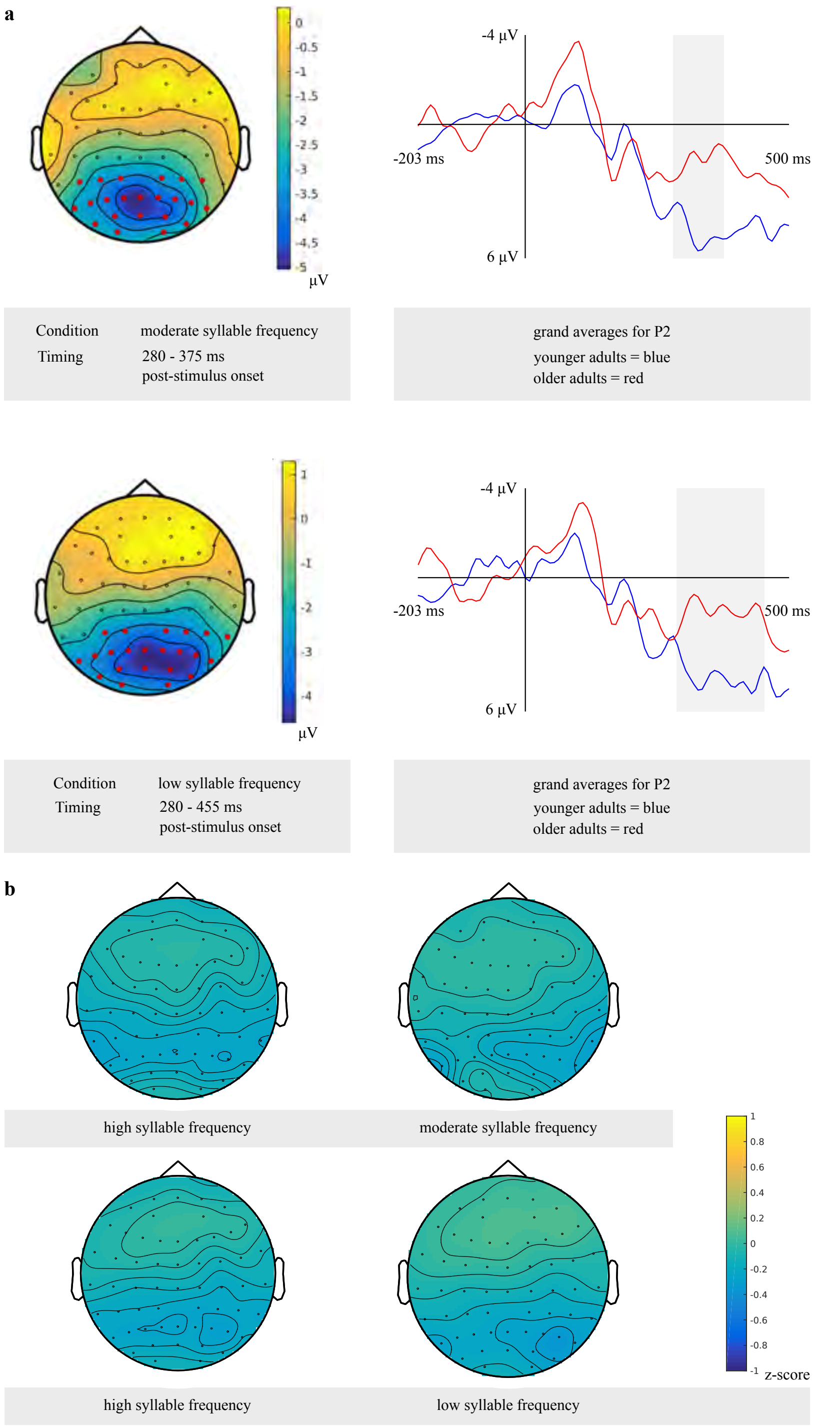

a
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
µV
-4 µV
-203 ms
500 ms
6 µV
Condition moderate syllable frequency
Timing 280 - 375 ms
post-stimulus onset
grand averages for P2
younger adults = blue
older adults = red
1
0
-1
-2
-3
-4
µV
-4 µV
-203 ms
500 ms
6 µV
Condition low syllable frequency
Timing 280 - 455 ms
post-stimulus onset
grand averages for P2
younger adults = blue
older adults = red
b
high syllable frequency
moderate syllable frequency
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
z-score
high syllable frequency
low syllable frequency

Figure 3.13a: Left: clusters related to the difference between younger and older adults identified in the stimulus-locked analysis for a moderate (top) and high syllable frequency (bottom) in the reading task targeting phonetic encoding. Electrodes included in the clusters are marked in red. Right: waveforms of the grand averages for the younger (in blue) and older adults (in red) for the electrodes P2.

Figure 3.13b: Scalp distributions for high and moderate syllable frequency (top) and for high and low syllable frequency (bottom) showing the z-scores of the older adults compared to the younger adults.

3.4 Discussion

The current study had two aims, which will be addressed in this discussion. The first was to identify the speech production stages in a group of older adults and in a group of younger adults. The second aim was to test whether the stages change with age with respect to the timing or regarding the neural configuration observed in the scalp distributions.

3.4.1 Identification of speech production stages

To identify the stages of the speech production process, a protocol with EEG was developed with three tasks tapping into four speech production stages. The manipulations in the tasks used to identify the stages had an effect on the response times in both the older and the younger adults. In the lemma retrieval task, the cumulative semantic interference effect caused increased response times for items belonging to the same category when they were presented at the fifth ordinal position compared to when they were presented at the first ordinal position. Also, later response times were found for items with a later AoA compared to items with an earlier AoA, as shown in the lexeme retrieval task. In the nonword reading task, nonwords that consisted of more phonemes used to track phonological encoding and nonwords with a lower syllable frequency used to tap into phonetic encoding caused increased response times. The results of the cluster-based permutation analysis of the EEG data revealed that the manipulations used in the tasks of the protocol showed an effect in particular time windows. First the time windows in the younger adults will be discussed, after which the time windows in the older adults will be addressed.

Younger adults

In the younger adults, the timing of the cumulative semantic interference effect was revealed from 100 to 265 ms after stimulus presentation and from 445 to 195 ms before response onset. Response-locked cumulative semantic interference effects have not been reported in previous studies using EEG. However, the stimulus-locked timing largely corresponded to the timing of this effect found by Maess et al. (2002) from 150 to 225 ms after stimulus presentation, but only partially overlapped with the timing of this effect found by Costa et al. (2009) from 200 to 380 ms after stimulus presentation. As our materials showed, the items used by Maess et al.

(2002) depicted mono- and disyllabic high frequency words. The materials used by Costa et al. (2009) also included longer and less frequent words, which may explain the later latency of the cumulative semantic interference effect.

The timing of the AoA-effect for the younger adults appeared from 100 to 300 ms after stimulus presentation. This result corresponds to the timing of this effect from 120 to 350 ms after stimulus presentation found by Laganaro and Perret (2011). Also, the response-locked effect for the younger adults from 475 to 330 ms before response onset overlaps with previously reported time windows of this stage from 380 after stimulus presentation up to 200 ms (Laganaro et al., 2012) or up to 100 ms before response onset (Valente et al., 2014).

Nonword length in phonemes was found to have an effect from 350 to 425 after stimulus presentation and from 335-320 before response onset for the younger adults. No previous speech production studies using EEG have reported on nonword-length effects. Word-length effects have been studied using picture-naming tasks, but no effects have been identified (Hendrix et al., 2017; Valente et al., 2014). In our study, a length effect was identified with a nonword-reading task. The input for phonological encoding of a word differs from the input for phonological encoding of a nonword, which may explain why the effect was found for nonwords, but not for words. The phonological encoding of a familiar lexeme likely required less effort than the phonological encoding of an unfamiliar string of phonemes.

The syllable frequency effect in the nonword-reading task has been identified after stimulus presentation from 350 to 450 ms for younger adults. Also, the effect has been found before response onset from 250 to 200 ms. Bürki et al. (2015), using syllable frequency effect in a nonword-reading task, identified this effect from 170 to 100 ms before response onset (Bürki et al., 2015). This effect was later than the effect found in the current study, most likely because the task required participants to insert a phoneme into the nonword as they read it, which complicated the task.

The time windows described in the previous paragraphs correspond to the speech production stages identified by Levelt et al. (1999) and Indefrey (2011). In the speech production model, lemma retrieval precedes lexeme retrieval. In the younger adults, the cumulative semantic interference effect and the AoA-effect started at the same time in the stimulus-locked analysis, but the AoA-effect lasted longer than the cumulative semantic interference effect. In the response-locked analysis, the cumulative semantic interference effect lasted longer than the AoA-effect. The time window for lexeme retrieval started before and ended during the time window for lemma retrieval. In the lexeme retrieval task, lemma retrieval was not manipulated and, thus, lemma retrieval was less demanding (and, hence, faster) in the lexeme retrieval task than in the lemma retrieval task. Therefore, the time window for lexeme retrieval in the lexeme retrieval task may have started earlier than the time window for lemma retrieval in the lemma retrieval task.

Lexeme retrieval is followed by phonological encoding in the model. For picture naming, the lexical route is used, whereas for nonword reading the sublexical route should be recruited.

Thus, the timing of the lexeme retrieval stage in the picture-naming task and the timing of the phonological encoding stage in the nonword-reading task cannot be compared using our method. Phonological encoding precedes phonetic encoding in the model. In the stimulus-locked analysis, the nonword-length effect started at the same time as the syllable frequency effect, but the length effect ended earlier. In the response-locked analysis, the nonword length in phonemes effect preceded the syllable frequency effect. Thus, the protocol can be used to identify the stages using EEG in the younger adults.

Older adults

In the older adults, the cumulative semantic interference effect was found from 540 to 450 ms before response onset. Since no response-locked cumulative semantic interference effects have been reported previously, the response-locked effect revealed in the older adults cannot be compared to other studies.

AoA-effects have previously been identified in response-locked time windows until 200 ms (Laganaro et al., 2012) or 100 ms before response onset (Valente et al., 2014). These time windows overlap with the response-locked effects for the older adults from 430 to 140 ms before response onset.

The effect of nonword length in phonemes was identified from 100 to 135 ms and from 280 to 300 ms after stimulus presentation for the older adults. This study is the first time that effects of nonword length in number of phonemes in an EEG study have been reported. 3

The second effect that was tested in the nonword-reading task was syllable frequency, which has been identified from 280 to 455 ms after stimulus presentation. This effect was found from 455 to 435 ms before response onset as well. The timing of these effects is earlier than the timing of the syllable frequency effect reported by Bürki et al. (2015). As said above, task was more demanding, which may explain these differences.

In the older adults, the response-locked cumulative semantic interference effect preceded the response-locked AoA-effect. This corresponds to the speech production processes identified by Levelt et al (1999) and Indefrey (2011), in which lemma retrieval precedes lexeme retrieval. In the older adults, the effect of nonword length in phonemes was identified before the syllable frequency effect, but there is an overlap of 20 ms in the stimulus-locked analysis. This finding is also in agreement with the model, because phonological encoding precedes phonetic encoding. Thus, the protocol can be used to identify the stages using EEG in the older adults as well.

3.4.2 Aging effects on speech production stages

The behavioral data showed that both the younger adults and the older adults performed at ceiling on every task. Thus, in contrast to the study by Connor et al. (2004), no reduced accuracy in picture naming was found for older adults. This can be explained by a major difference in the age range of the participants in both studies: it was larger in the study by Connor et al. (2004: from 30 to 94 years) than in the current study, from 17 to 65 years. A behavioral difference between the groups was found in the response times. The older adults responded later than the younger adults on every task. It was hypothesized that the later response times of the older adults should reflected in the timing of the speech production stages in the EEG data.

Differences in timing between younger and older adults

Lemma retrieval requires semantic memory to activate the target-lemma node along with its semantically-related neighbors. These neighbors are inhibited to select the target lemma. Since both semantic memory (Cardenas et al., 2011; Harada et al., 2013) and inhibition (Harada et al., 2013) decline with aging, the duration of the lemma retrieval stage was expected to be increased in older adults. This hypothesis was not supported, because the lemma retrieval stage lasted 90 ms in the older adults, while in the younger adults, its duration was 165 ms in the stimulus-locked analysis and 250 ms in the response-locked analysis. However, all time windows of the effects that were found in the older adults were shorter than the time windows of the effects found in the younger adults. In older adults, neurons that fire together are possibly less synchronous in their timing, less aligned regarding their geometry or the effect has a more variable latency (Wlotko et al., 2010). Therefore, the time window in which all participants show an effect is shorter.

Since the duration of lemma retrieval was expected to be increased, the onset of the next stage, lexeme retrieval, was expected to be delayed in the older adults. This hypothesis was supported. The response-locked effect started 45 ms later for the older adults compared to the younger adults. Also, an increased duration of the lexeme retrieval stage was hypothesized, because of the tip-of-the-tongue phenomenon, which is observed more frequently in older adults (Shafto et al., 2007). No increased duration was found, which again can be explained by the reduction of the effect caused by the effect's variability within and between the older adults (Wlotko et al., 2010).

The stages of the sublexical route were expected not to be delayed in older adults. There have been no previous studies on aging's effect on phonological encoding. Also, older adults have not revealed longer response times producing alternating syllable strings, which require more effort during phonetic encoding, than for the production of sequential syllable strings (Tremblay and Deschamps, 2016). However, both the effect of nonword length in phonemes related to phonological encoding and the syllable frequency effect targeting phonetic encoding, started earlier for the older adults than for the younger adults. The difference in the onset of the timing of these stages between the groups is quite large, hence, this difference cannot be explained by the effect's variability in older adults.

Neurophysiological differences between younger and older adults

There were differences between younger and the older adults regarding the time windows in which effects that were related to the stages were found. Results of the cluster-based permutation analyses showed that for every stage in at least one time-window, differences between younger and older adults were found. In the time windows in which the younger adults showed a cumulative semantic interference effect, an AoA effect or an effect of nonword length in number of phonemes, no such effect was observed in the older adults. This finding shows that the older adults had a different timing for the speech production stages than the younger adults. Despite partially overlapping time windows for the syllable frequency effect in the younger and older adults, a difference between both groups was found. The overlap in timing was possibly too short, so both groups differed during the majority of the time window, or the neural configuration of the syllable frequency effect differed between the groups. Except for the response-locked time windows identified using the cumulative semantic interference effect, differences between younger and older adults were generally identified in stimulus-locked time windows. When the stimulus is presented, the first process is the visual analysis of the picture or the nonword. This process is assumed to be identical in both age groups, because the efficiency of the visual network is not expected to change with age (Geerligs et al., 2015). After that, higher cognitive function networks, such as CON and FPCN are involved in the speech production stages. A decrease of the local efficiency of these networks may alter their neural signature or change their timing, which is reflected in the EEG data. Even though the older participants in the study by Geerligs et al. were on average almost a decade older than the older adults in our study, our older participants may have a mild decrease in local efficiency and modularity in the CON and the FPCN compared to the younger adults, because the decrease is not linear with age (Geerligs et al., 2015).

An overview of the timing of the stages in the younger and older adults and the timing of significant differences between the two groups is provided in Figure 3.14.

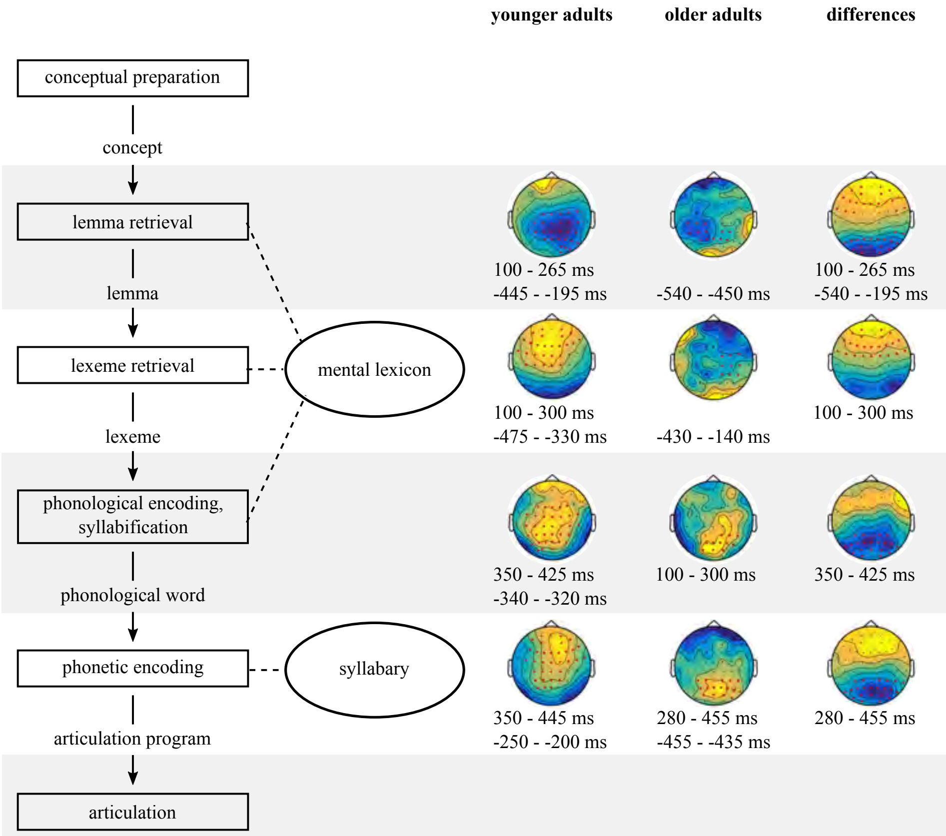


Figure 3.14: Timing of the stages in the model of spoken word and nonword production based on the results of the younger and the older adults and their differences.

Apart from the timing of the speech production stages, the neural configurations of the scalp distributions of the stages have been compared between the older and the younger adults. It was hypothesized that the scalp distributions do not change with age, because the same groups of neurons are expected to be involved in the stages of speech production in neurologically healthy adults, regardless of the adults' age. Despite the fact that the effects related to each stage have been found in different time windows in the two groups, the scalp distributions during the stage were identical in the older and younger adults. This uniformity was the case for each speech production stage. Therefore, it can be concluded that older adults used the same neuronal processes as younger adults in the speech production stages. This was also supported by our behavioral results. Like the younger adults, the older adults performed at ceiling on the tasks. Also, the response times showed that the manipulations used in the tasks had the same effects in older and younger adults. Thus, the same factors had an influence on the speech production stages in both age groups.

The question remains why the response times of the older adults were later than the response times of the younger adults, even though the timing of the effects used to target the speech production stages was not generally delayed in the older adults. In the lexical route, lexeme retrieval was found to be delayed in older compared to younger adults. Since both picture-naming tasks required lexeme retrieval, the delay before this stage may have resulted in longer response times on the lemma and lexeme retrieval tasks. This is in line with the findings in the study by Laganaro et al. (2012) revealing differences between slow and fast speakers before the time window in which the AoA-effect was found.

Lexeme retrieval is not involved in nonword production Therefore, delayed lexeme retrieval cannot explain later response times on nonword tasks in older adults, while no delay was observed for the phonological and phonetic encoding stages. Maybe, older adults respond later, because they generally are slower, as suggested in the Global Slowing Hypothesis (e.g. Brinley, 1965). However, this should have been reflected in the EEG data as a longer duration and a later onset for every speech production stage, because neurophysiological measures are more sensitive than response time measures. Participants were asked to name the items as fast and accurately as possible. The tasks were fairly easy, so the accuracy of all individuals with aphasia was at ceiling. While younger adults can respond fast and accurately at the same time, older adults are known to focus on either speed or accuracy (Ratcliff et al., 2007). Maybe older adults focused more on accuracy in our study and, therefore, needed to collect more information before they were ready to respond (Rabbitt, 1979). In that case, the processes may not have been delayed in general, but only the decision whether the response was accurate or not was delayed. Thus, after the speech production process has been planned to its final stage, articulation, the older adults may have waited longer than the younger adults until they responded. In that case, this effect is not visible on the EEG data, but only reflected in longer response times. If older adults wait before responding, the response-locked effects should be identified earlier in the older adults than in the younger adults. This, indeed, was the case for the cumulative semantic interference effect and the syllable frequency effect, but not for the AoA-effect. However, individual differences are known to modulate the time window of the AoA effect (Laganaro et al., 2012). A possible modulation of the AoA-effect is supported by our response time data, in which the older adults showed a smaller AoA-effect than the younger adults.

3.5 Conclusion

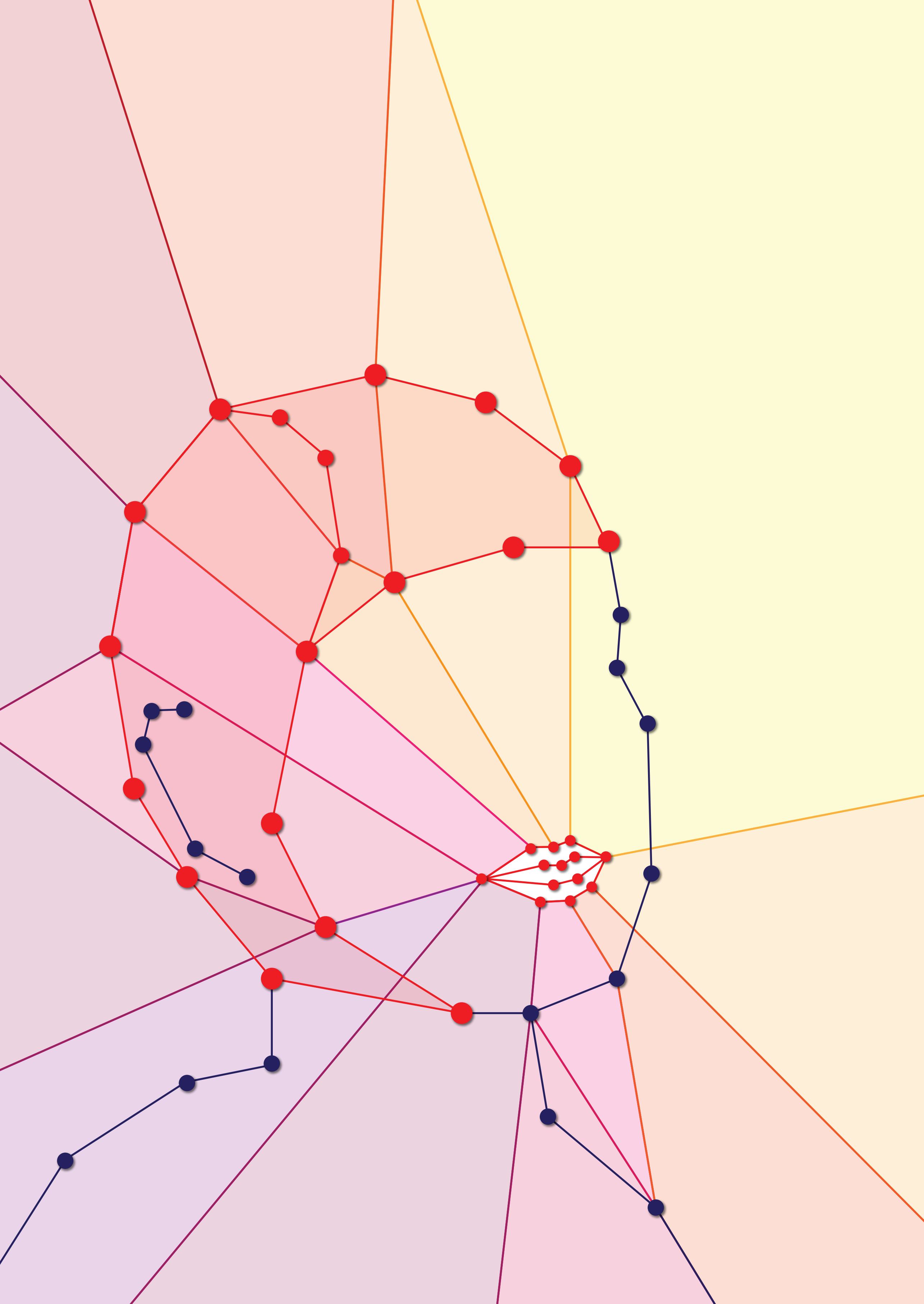
To conclude, the stages of the speech production process have been successfully identified in older and younger adults using the tasks of the protocol with EEG. The manipulations in the tasks had the same effect on the response time in both age groups, thus the same factors influenced the speech production stages. Also, the scalp distributions related to the speech production stages did not differ between the older and the younger adults. This shows that the same neural processes are used during the speech production stages.

However, behaviorally, the comparison of the older and the younger adults showed that the older adults required longer response times on all tasks. Yet, the EEG results showed that the speech production stages do not generally start later or last longer in the older adults compared to the younger adults.

3.6 Limitations

The study is subject to two potential limitations. In this study, we included older adults (40-65 years old), whereas it is common practice to compare younger adults (i.e. university students) to a group of elderly (usually over 70 years old). Thus, the age difference between the younger and older adults was smaller than in other studies that compare language production and, therefore, the aging effects found in the current study are potentially not as large as may have been found if we had compared younger and elderly adults. A comparison between the older adults included in our study and individuals with aphasia is possible: individuals with aphasia and without concomitant cognitive disorders are usually within the age range of our group of older adults. However, it would be very interesting to compare the performance of both age groups of the current study with healthy elderly and individuals with dementia, who usually above 70 years old.

Secondly, nonword reading-skills of the two groups included in the present study have not been assessed prior to the experiment. Reading was only assessed using self-report, which cannot be used to detect potential variation in reading skills. This potential variation may have had an effect at the phonological and phonetic encoding stages. We do not think this caveat influenced the results, however, because all participants performed at ceiling on the nonword-reading task.



Chapter 4

Distinguishing a phonological encoding disorder from Apraxia of Speech in individuals with aphasia by using EEG

4.1 Introduction

Aphasia is an acquired language disorder, caused by focal brain injury that arises after language acquisition has been completed (Bastiaanse, 2010a). In aphasia, impairment may occur at different speech production stages. These stages can be described in a model of speech production (Levelt, Roelofs, & Meyer, 1999, see Chapter 1). A disorder of lemma retrieval may cause semantic paraphasias (Howard & Orchard-Lisle, 1984), while a disorder of lexeme retrieval will lead to word finding problems, such as omissions (e.g. Howard & Gatehouse, 2006). Lexeme frequency and age of acquisition (AoA) of the words play an important role in lexical retrieval in aphasia (Bastiaanse, Wieling, & Wolthuis, 2016; Kittredge, Dell Verkuilen, & Schwartz, 2008; Nickels & Howard, 1995). Phonemic paraphasias[11] or speech sound errors may occur due to a disorder in phonological and/or phonetic encoding. During phonological encoding, the phonemes corresponding to the lexeme are retrieved and ordered and the phonological rules are applied (Levelt et al., 1999). According to Ellis and Young (1988), aphasic individuals with a disorder at this level (that they call 'phoneme level') have more problems with longer words than with shorter words. Individuals with Apraxia of Speech (AoS) are hypothesized to have problems arising during programming of an articulation plan, that is, during phonetic encoding (Darley, Aronson, & Brown, 1975; Miller & Wambaugh, 2017; Ziegler, 2008). Syllable frequency plays a role during phonetic encoding and, hence, in AoS (Aichert & Ziegler, 2004; Laganaro & Alario, 2006). Effects of syllable frequency have also been observed in neurologically healthy individuals: high frequency syllables are processed faster than low frequency syllables (Laganaro & Alario, 2006; Levelt & Wheeldon, 1994). According to Levelt and Wheeldon (1994), articulation plans for high frequency syllables are stored and articulation plans for low frequency syllables need to be programmed on demand before articulation takes place. Varley, Whiteside and Luff (1999) state that not only high frequency syllables, but also high frequency multisyllabic words and clauses can be stored. Varley, Whiteside, Windsor, & Fisher (2006) argue that the activation of stored articulation plans is affected in AoS and, therefore, comparable difficulties are observed in phonetic encoding of high and low frequency words in individuals with AoS, because articulation plans need to be programmed for both types of syllables (see also: Varley & Whiteside, 2001; Whiteside and Varley, 1998). However, the retrieval of extremely high frequency words may be preserved in AoS (Varley et al., 2006). Aichert and Ziegler (2004) found that lower frequency syllables were more impaired than extremely high frequency syllables, and also suggested that the retrieval of motor plans is impaired in AoS. Laganaro (2005, 2008) showed that a syllable frequency effect may also occur in individuals with a phonological impairment who were not suffering from AoS. This can be explained by the interaction between the phonological and

[11] In this dissertation, the term 'phonemic paraphasia' is used as a broad term to encompass both phonetic and phonological impairment whilst acknowledging that in the case of phonetic encoding impairments/AoS the errors may not involve 'phoneme sized' units.

the phonetic encoding stage. If a lack of phonological information prevents the activation of a syllable during phonological encoding due to a disorder in this stage, a high frequency syllable that is already active at the level of phonetic encoding is possibly selected. Apart from that, the production of high frequency syllables is facilitated through feedback from the phonetic encoding stage. Therefore, an aphasic individual with a phonological disorder may replace low frequency syllables with high frequency syllables and, thus, a syllable frequency effect is observed.

4.1.1 Differentiating phonological and phonetic encoding disorders

AoS is usually accompanied by nonfluent aphasia, but can also occur with fluent aphasia (Nicholas, 2005). Therefore, phonological and phonetic encoding disorders are difficult to differentiate in linguistic terms in individuals with aphasia (Ballard et al., 2016; Den Ouden, 2002; but see Bastiaanse, Gilbers, & Van der Linde, 1994; Gilbers, Bastiaanse, & Van der Linde, 1997). There are two ways to differentiate between a phonological encoding impairment and AoS. First, characteristics observed in the speech can be used to distinguish the disorders. There is an overlap in characteristics that can be observed in both a phonological encoding disorder (PED) in aphasia and AoS, but some characteristics specific to AoS can be identified (Ballard et al., 2016; Jonkers, Feiken, & Stuive, 2017). Examples of these typical characteristics of AoS are the segmentation of syllables and consonant clusters into phonemes by inserting pauses (Kent & Rosenbek, 1983). As Jonkers et al. (2017) indicate, there is discussion about the characteristics that can be observed in both a PED in aphasia and AoS, such as the effect of articulatory complexity, the production of more errors with consonants than with vowels and the inconsistency of the errors. For example, in both a PED in aphasia and in AoS more errors are observed in the production of words with increased articulatory complexity (Canter, Trost, & Burns, 1985). In the production of phonemes, more errors may arise when producing consonants compared to producing vowels in both groups (Caramazza, Chialant, Capasso, & Miceli, 2000; Miller & Wambaugh, 2017). Also, the production of the same phoneme may be accurate on one occasion and inaccurate on another occasion in both groups (Bislick, McNeil, Spencer, Yorkston, & Kendall, 2017; Haley, Jacks, & Cunningham, 2013). Thus, a characteristics-based differentiation is not optimal, although Jonkers et al. (2017) showed that if a combination of at least 3 out of 8 typical characteristics occur in the speech of an aphasic individual, the diagnosis of AoS is confirmed in 85% of the cases.

The location of the brain lesion cannot be used to differentiate between aphasia and AoS. AoS has been related to a lesion in the insula, a lobe inside the Sylvian fissure (Dronkers, 1996; Moser, Basilakos, Fillmore, & Fridriksson, 2016; Richardson, Fillmore, Rorden, LaPointe, & Fridriksson, 2012; Square-Storer, Roy, & Martin, 1997). A lesion in the perisylvian area, located around the Sylvian fissure, has been related to both AoS and aphasia (Moser et al., 2016). Cases of severe AoS showed lesions in both the insula and in Broca's area (Ogar et al., 2006). A lesion in Broca's area has often been related to AoS (Bonilha, Moser, Rorden, Baylis, & Fridriksson, 2006; Hillis et al., 2004; Richardson et al., 2012; Square-Storer et al., 1997; Trupe et al., 2013). Damage to the arcuate fasciculus, which connects Broca's area to Wernicke's area, has been related to conduction aphasia (Catani & Mesulam, 2008), which is typically associated with a PED (Geschwind, 1974). Thus, also the site of the brain lesion is not a perfect way to differentiate the disorders, because there is an overlap in sites that can be related to both aphasia and AoS.

All in all, speech sound errors can arise due to an impairment to phonological as well as phonetic encoding and, clinically, these impairments are hard to distinguish (Laganaro, 2012). However, since the underlying impairments are different, they should be treated differently. Therefore, it is clinically important to find a way to distinguish the origin of the deficit. To this purpose, we conducted an EEG study. EEG has been successfully applied to distinguish between impairments in lemma and lexeme retrieval previously (Laganaro et al., 2009), but they did not attempt to distinguish a phonological disorder from AoS by using EEG (Laganaro, Python, & Toepel, 2013).

4.1.2 Neurophysiological changes in EEG

The speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding have their own timing. An overview of various EEG and MEG studies provided evidence for the timing of the individual stages (Indefrey & Levelt, 2004; Indefrey, 2011). All four stages have also been identified in one and the same group of non-brain-damaged adults using a protocol with EEG (Den Hollander, Jonkers, Mariën, & Bastiaanse, 2019, see Chapter 3). After a stroke, changes are observed in the EEG data (Laganaro, Morand, Michel, Spinelli, & Schnider, 2011). In the time window of the impaired speech production stage, different patterns have been found in the EEG data for individuals with aphasia as compared to neurologically healthy adults (Laganaro et al., 2009, 2013).

The speech production stages in the model described by Indefrey and Levelt (2004) were used to indicate the impaired stage in the individuals with aphasia that participated in the study by Laganaro et al. (2009). According to Laganaro et al. (2009), phonological encoding comprises the stages that are referred to as lexeme retrieval and phonological encoding in the current study. This difference between the current study and the study by Laganaro et al. (2009) has an impact on the speech production stage in which the impairment is identified in the individuals with aphasia. The individuals with a phonological disorder described in the study by Laganaro et al. (2009) have an impairment in the retrieval of the phonological word form, thus in lexeme retrieval. The time window in which the EEG data of the individuals with aphasia and the non-brain-damaged adults differed corresponds to the time window of the lexical frequency effect observed in non-brain-damaged individuals in the same study. Variation in lexical frequency has an impact on lexeme retrieval.

EEG can be used to differentiate between a semantic and a lexical disorder in individuals with aphasia (Laganaro et al., 2009). Differences between individuals with a semantic disorder (at or before the lemma retrieval stage) and non-brain-damaged individuals were found to have an earlier onset in the EEG data than differences between individuals with a lexical disorder (at the lexeme retrieval stage) and non-brain-damaged individuals using a picture naming task. In both groups of individuals with aphasia, the EEG data of correct and erroneous trials were very similar. In a later time window in the EEG data, individuals with a phonological disorder and/or AoS (at the phonological and/or phonetic encoding stage) have been found to differ from non-brain-damaged individuals using a picture naming task and a word reading task (Laganaro et al., 2013). However, with this paradigm it was not possible to distinguish between a phonological encoding deficit and AoS. Also, in a nonword reading task, differences in the EEG data were observed between two individuals with AoS and non-brain-damaged individuals (Laganaro, 2011). Therefore, EEG seems to be a promising method to identify the speech production stage at which aphasia and AoS occur. In the studies by Laganaro (2011) and Laganaro et al. (2013), one separate speech production stage was studied in a group of individuals with aphasia. In the current study, all four speech production stages were studied in two groups of individuals with aphasia. This made it possible to test for whether each speech production stage was impaired or intact. Also, the group of participants with AoS in this study was larger than in the study by Laganaro (2011). Finally, while previous studies have been conducted with French speaking participants, the participants in the current study were native speakers of Dutch. Dutch has a different phonology and allows for more complex consonant clusters than French, which has an impact on the characteristics observed in individuals with AoS (Jonkers, Terband, & Maassen, 2014).

4.1.3 Current study

In the current study, a protocol with EEG was used to distinguish individuals with aphasia and a PED from individuals with aphasia and AoS. This protocol has previously been used to identify the speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding in younger and older adults (Den Hollander et al., 2019). The tasks used to target lemma and lexeme retrieval were picture naming tasks, while phonological and phonetic encoding were identified using a nonword reading task. Lemma retrieval was studied using the effect of the number of previously named pictures of a particular semantic category, known as the 'cumulative semantic interference effect' (Costa, Strijkers, Martin, & Thierry, 2009; Howard, Nickels, Coltheart, & Cole-Virtue, 2006; Maess, Friederici, Damian, Meyer, & Levelt, 2002). When the number of previously named pictures of a particular semantic category increases, retrieving a lemma belonging to that particular semantic category increases the processing cost. The Age of Acquisition-effect was used to target lexeme retrieval (Laganaro & Perret, 2011; Laganaro, Valente, & Perret, 2012; Valente, Bürki, & Laganaro, 2014). The processing cost required to retrieve a lexeme increases with the age at which the word corresponding to the lexeme was acquired. Phonological encoding was tracked using the length in number of phonemes effect in nonwords. An increase in number of phonemes in a word enlarges the processing cost required during phonological encoding. The syllable frequency effect in nonwords was used to study phonetic encoding (Bürki, Pellet-Cheneval, & Laganaro, 2015; Laganaro, 2011). The processing cost required for phonetic encoding increases with decreasing syllable frequency. Stimulus-locked and response-locked analyses were used to track the different stages (Laganaro, 2014). In the older adults, comparable in age and education with the group of brain-damaged individuals of the present study (see Chapter 3), lemma retrieval was identified from 540 to 450 ms before response onset and lexeme retrieval was identified from 430 to 140 ms before response onset. Phonological encoding was identified from 100 to 300 ms after stimulus presentation and phonetic encoding was identified from 280 to 455 ms after stimulus presentation and from 455 to 435 ms before response onset. The model and an overview of the identified stages are presented in Figure 4.1.

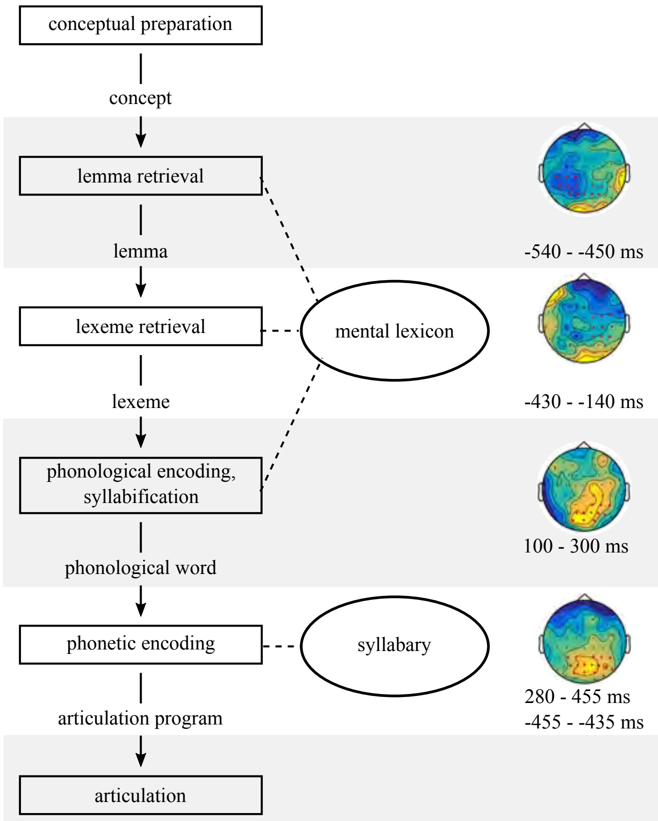


Figure 4.1: The model of spoken word and nonword production based on Levelt, Roelofs, & Meyer (1999) and Indefrey & Levelt (2004) along with the timing of the stages and a scalp distribution observed in that time window based on the EEG data of the older adults reported in Den Hollander et al. (2019).

The individuals with aphasia included in the current study produced speech sound errors. However, the underlying disorder responsible for their speech sound errors could have been either phonological in nature or AoS. The aim of the project was to develop a protocol with EEG that can be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS. Hence, three different analyses were carried out.

In the first analysis, the goal was to use EEG to identify the lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding stages in the individuals with aphasia. The research question was whether all stages could be identified by using EEG in both groups of individuals with aphasia. In previous EEG studies (e.g. Laganaro et al. 2009, 2013), the speech production stage was not tracked in individuals with aphasia, but in the NBDs only. Individuals with aphasia were then compared to the NBDs on that speech production stage. Hence, we could not hypothesise based on these studies. We successfully identified the four stages using EEG and the same tasks in neurologically healthy individuals (Den Hollander et al., 2019). Therefore, it was hypothesized, that the cumulative semantic interference effect and the AoA effect would be observed in the accuracy, response time and EEG data of the individuals with aphasia recorded during the picture naming tasks targeting lemma and lexeme retrieval. Also, the effect of nonword length in phonemes and the syllable frequency effect were expected to be observed in the accuracy, response time and EEG data of the individuals with aphasia recorded during the nonword reading task targeting phonological and phonetic encoding.

The second analysis was carried out to identify differences between the individuals with aphasia and matched non-brain-damaged individuals at every stage. The research question was at which stages individuals with aphasia and a PED and individuals with aphasia and AoS differed from matched non-brain-damaged individuals. Both phonological and phonetic impairments have an impact on picture naming and nonword reading tasks. Thus, individuals with aphasia were expected to have lower accuracy and slower response times compared to the non-brain-damaged individuals on every task. It was hypothesized that differences between the individuals with aphasia and the non-brain-damaged individuals would be observed in the EEG data at the stages that were impaired in the individuals with aphasia (e.g. Laganaro, 2011; Laganaro et al. 2009, 2013).

Pure conduction aphasia and pure AoS are rare, therefore, inevitably, the majority of the participants also suffered from word finding difficulties. Their word finding difficulties were caused by lemma or lexeme retrieval problems. Distinguishing an impairment in lemma retrieval from an impairment in lexeme retrieval is complicated (e.g. Howard & Gatehouse, 2006). Therefore, the aphasic participants were expected to differ from non-brain-damaged individuals at the lemma retrieval stage or at the lexeme retrieval stage. The aphasic individuals with a PED were expected to differ from the non-brain-damaged individuals at the phonological encoding stage. No differences were expected to be found between the aphasic individuals with a PED and the non-brain-damaged individuals during phonetic encoding.

Only the individuals with aphasia and AoS were expected to differ from the non-brain-damaged individuals at the phonetic encoding stage.

Both groups of individuals with aphasia were not expected to show behavioural differences on the picture naming tasks as most of them suffered from word finding difficulties. Differences between the groups of individuals with aphasia were hypothesized to be observed on nonword reading, because this task targeted their impaired stage. Therefore, nonword reading was the most difficult task for them, so they could not simultaneously respond quickly and accurately. The responses of the individuals with aphasia and a PED were either more accurate and slower or faster and less accurate than the responses of the individuals with aphasia and AoS, which is known as the 'speed-accuracy tradeoff' (Brinley, 1965; Ratcliff, Thapar, & McKoon, 2007). Given that participants had 5 seconds to respond until the next stimulus was presented, they needed to respond quickly. Phonological encoding takes less time than phonetic encoding in healthy adults (Indefrey, 2011). So, if the impairment, for example, doubled the time required for the process, individuals with a PED had more time to prepare the response than individuals with AoS. Hence, the individuals with AoS were expected to have lower accuracy than individuals with a PED.

To ensure that differences other than the level of impairment between the groups of individuals with aphasia impacted on the EEG results, the groups of individuals with aphasia were not compared directly. Instead, differences between individuals with aphasia and a PED and their matched non-brain-damaged individuals were compared to the differences between individuals with aphasia and AoS and their matched non-brain-damaged individuals. The individuals with aphasia and AoS had an impairment at the phonetic encoding stage, whereas the individuals with aphasia and a PED did not. Therefore, it was expected that differences between these groups would be found at the phonetic encoding stage only.

4.2 Methods

4.2.1 Participants

Sixteen individuals with aphasia due to a single stroke in the left hemisphere participated in this study. Five individuals were diagnosed by their speech therapist with a primarily PED (4 males) and had an average age of 62.4 years (range: 51-76). They will be referred to as 'individuals with a PED'. They were matched on gender, age and education with five non-brain-damaged individuals (4 males) with an average age of 60 years (range: 53-65). Eleven individuals were diagnosed with AoS in addition to aphasia (8 males) and had an average age of 61.6 years (range: 46-70). They will be referred to as 'individuals with AoS'. They were matched on gender, age and education with eleven non-brain-damaged individuals (6 males) with an average age of 59 years (range: 43-65). The non-brain-damaged individuals, who will be referred to as 'NBDs', were selected from the group of older adults in the study by Den Hollander et al. (2019). All participants were right-handed based on a handedness questionnaire (Oldfield, 1971) and native speakers of Dutch. They signed a written informed consent prior to the experiment. The study was approved by the Medical Ethics Committee of the University Medical Center Groningen (UMCG) and the *Ethics Committee of Humanities* of the University of Groningen.

The aphasic speakers were selected by experienced Speech and Language Therapists. The primary characteristic of their speech production was the use of speech sound errors. Aphasia had been diagnosed using the Dutch version of the Comprehensive Aphasia Test (Swinburn, Porter, & Howard, 2005; CAT-NL: Visch-Brink, Vandenborre, de Smet, & Mariën, 2014) or the Dutch version of the Aachen Aphasia Test (Graetz, de Bleser, & Willmes, 1992). To assess the severity of the speech production impairment, all aphasic speakers were tested with the word and nonword repetition task of the Dutch version of the PALPA (Kay, Coltheart, & Lesser, 1992; Dutch version: Bastiaanse, Bosje, & Visch-Brink, 1995). Based on the data of neurologically healthy speakers provided with the PALPA, a score of less than 24 on the word repetition task (maximum score = 24) and a score of less than 28 on the nonword repetition task (maximum score = 30) indicates an impairment. The demographics of the aphasic speakers along with their scores on the language production tasks of the CAT or the AAT and the scores on the PALPA tasks are provided in Appendix 7. When the Speech and Language Therapist thought that the aphasic speaker suffered from AoS, this diagnosis had to be confirmed by the Dutch Diagnostic Instrument for Articulation Disorders (DIAS; Feiken & Jonkers, 2012). In Appendix 8, DIAS scores of the aphasic speakers with AoS are provided.

4.2.2 Materials

4

Lemma retrieval

Black-and-white drawings were used in the lemma retrieval task. The pictures originated from the *Auditief Taalbegripsprogramma (ATP;* Bastiaanse, 2010b) and the *Verb and Action Test (VAT;* see Bastiaanse et al., 2016) for individuals with aphasia. The order in which the depicted nouns were presented was manipulated for the cumulative semantic interference effect. The pictures were grouped in sets of five semantically-related neighbors (e.g., bed, couch, cradle, closet, chair) that fit into a particular category (e.g., furniture, clothes, insects). The depicted nouns were all mono- or disyllabic in Dutch. The same number of syllables and the same stress pattern was used for the five nouns within one category. Also, the nouns were controlled for logarithmic lemma frequency in Dutch (Baayen, Piepenbrock, & Gulikers, 1995).

A picture-naming task was carried out by four participants (one male) with a mean age of 22 years, (age range: 21-23 years) for the selection of final items. Items that were named incorrectly by more than one participant were removed. The 125 items selected were 105 monosyllabic and 20 disyllabic nouns with an overall name agreement of 91.4% and an overall mean logarithmic lemma frequency of 1.28 (range: 0-2.91). The items are provided in

Appendix 1. To avoid an order of appearance effect the same set of pictures was used in two lists with reversed conditions. The lists were presented in three blocks of 30 items and one block of 35 items.

The pictures were presented on a computer screen. Participants were asked to name the pictures as quickly and accurately as possible. A black fixation cross on a white background was shown for 500 ms before the picture was presented. The function of the fixation cross was to draw attention and to announce that a picture was presented soon. The picture was shown for 5 seconds. Items within one category were not presented directly after another.

Lexeme retrieval

The pictures for this test originated from the same sources as the materials on the lemma retrieval task and represented mono- and disyllabic nouns in Dutch. Items were controlled for AoA (Brysbaert, Stevens, De Deyne, Voorspoels, & Storms , 2014) and lexeme frequency (Baayen et al., 1995).

For pretesting the materials, four participants (one male) with a mean age of 20.7 years (age range 19-22) took part in a picture naming task. These participants had not taken part in the lemma retrieval task. Items that were named incorrectly by more than one participant were omitted.

The 140 items selected were 87 monosyllabic and 53 disyllabic nouns with an overall name agreement of 93.9%. AoA ranged from 4.01 years for the noun 'book' to 9.41 years for the noun 'anchor', with a mean of 5.96 years. The mean logarithmic lexeme frequency was 1.02 (range: 0-2.44). The correlation between AoA and lexeme frequency in the items was significant ($r(138) = -.28$, $p < .001$). Therefore, in the analysis, only AoA has been taken into account. The items, which are provided in Appendix 2, were organized in one list including four blocks of 35 items. Every participant named the items in a different order, because the order of the items was randomized per block.

The procedure of the lexeme retrieval task was the same as the procedure of the lemma retrieval task. Since there was some item overlap between the lemma and lexeme retrieval tasks, the two tasks were never administered consecutively. A nonword task was always administered in between.

Phonological and phonetic encoding

To identify the stages of phonological and phonetic encoding, a nonword reading task was used. The reason why this task was used was discussed in Chapter 2. All nonwords were disyllabic. The combination of the two existing Dutch syllables resulted in a nonword, e.g. 'kikkels' or 'raalkro'. The spoken syllable frequency of the nonwords ranged from 250 to 5000 per million syllables (Nederlandse Taalunie, 2004). Two lists of nonwords were developed in written form for the reading task. The two lists contained the same syllables, but the syllables were combined differently, thus the nonwords were unique.

The nonwords were pretested in a reading task by four participants who took part in pretesting the picture naming tasks as well. Each list was pretested with two participants. The 140 selected items for List 1 had an accuracy rate of 100%; 8% of the 140 nonwords in List 2 were produced incorrectly. The syllables used in these items were combined into new nonwords. These nonwords were pretested again with two other participants. Their accuracy was 100%.

The duration of phonological encoding may increase with the number of phonemes and, therefore, the nonwords were controlled for the number of phonemes. For both lists, the number of phonemes in the nonwords ranged from 3 to 8. The average number of phonemes was 5.33 for List 1 and 5.29 for List 2. For each nonword, the average spoken syllable frequency was computed over its two syllables. The mean syllable frequency was 1136 per million syllables (range: 257-4514) for List 1 and 1077 per million syllables (range: 257-4676) for List 2. List 1 consisted of 47 nonwords with low, 41 nonwords with moderate and 52 nonwords with high spoken syllable frequency. The mean spoken syllable frequencies were sequentially 359 (range: 257-479), 705 (range: 515-965) and 2178 (range: 1017-4514) per million syllables. List 2 contained 47 nonwords with low, 43 nonwords with moderate and 50 nonwords with high spoken syllable frequency. The mean spoken syllable frequencies were respectively 359 (range: 257-486), 702 (range: 521-979) and 2075 (range: 1032-4676) per million syllables. Hence, the spoken syllable frequencies of the items were above the mean spoken syllable frequency for Dutch of 231 per million syllables, but Levelt and Wheeldon (1994) found a syllable frequency effect despite using a cutoff between high and low syllable frequency that was above the mean frequency. The two lists of nonwords are provided in Appendix 3.

The nonwords were presented in white letters on a black background. The font type Trebuchet MS Regular, size 64 was used. The stimulus was presented for 5 seconds and preceded by a fixation cross which was presented for 500 ms. Participants read either List 1 or List 2. Each list was divided into four blocks of 35 items. None of the participants read the nonwords in the same order, because the order in which the nonwords were presented was randomized per block. Participants were instructed to read the nonwords aloud as quickly and accurately as possible.

General procedure

During the experiments, participants were seated approximately 70 cm from the screen. E-Prime (E-Prime 2.0, 2012) was used to present the stimuli and to record the response times and the responses. A voice key was used to detect the response times. The responses were recorded using a microphone that was attached to a headset. Before the experiment started, participants practiced the task with five items for the picture naming tasks and with eight items for the nonword reading task. Participants had the opportunity to take a short break between the four blocks of the experiments.

EEG data recording

EEG data were recorded with 128 Ag/AgCl scalp electrodes (WaveGuard) cap using the EEGO lab system (ANT Neuro Inc., Enschede, The Netherlands). The electrode sites were distributed over the scalp according to the 10-5 system (Jasper, 1958). Bipolar electrodes were used to record vertical ocular movements, such as eye blinks, for which the electrode sites were vertically aligned with the pupil and located above and below the left eye. Also, horizontal ocular movements were recorded, for which the electrodes were horizontally aligned with the pupil and located on the right side next to the right eye as well as on the left side next to the left eye. Impedance of the skin was kept below 20 kΩ, which was checked before every experiment. Data were acquired with a sampling rate of 512 Hz and reference was recorded from the mastoids.

4.2.3 Data processing and analysis

Behavioral data

As the speech onset time detected by the voice key was not sufficiently exact (see: Den Hollander, Bastiaanse, & Jonkers, 2017), the audio recordings of the participants' responses were used to determine the speech onset time. The speech onset time in each audio file was manually determined using the waveform and the spectrogram in Praat (Boersma & Weenink, 2018). The speech onset times based on the audio files were used as response events in the response-locked EEG analysis. ANOVA's in R were used for the statistical analysis of the behavioral and item data (R Core Team, 2017). Accuracy data were analyzed on the same number of items per condition.

Items to which many NBDs responded extraordinarily fast or slow[12] were excluded from the EEG data analysis (lemma retrieval: 8%; lexeme retrieval: 18.6%; phonological and phonetic encoding: 12.1%). Trials to which NBDs responded incorrectly were excluded from the analysis (lemma retrieval: 7.8%; lexeme retrieval: 7.3%; phonological and phonetic encoding: 1.9%), which is common practice (e.g. Laganaro & Perret, 2011). Also, responses that included hesitations or self-corrections qualified as errors (lemma retrieval: 2.6%; lexeme retrieval: 2.6%; phonological and phonetic encoding: 0.8%).

The selection procedure of trials in the data of the aphasic speakers was different from the selection procedure of trials in the data of the NBDs. If only correct responses from the aphasic speakers would have been included in the analysis, the number of included trials would have reduced statistical power. Erroneous trials can be included, because the EEG response measured in erroneous trials does not differ from the EEG recorded in correct trials in aphasic speakers (Laganaro et al., 2009). Therefore, for the aphasic individuals, only trials with missing

[12] Fast response times were faster than 600 ms after stimulus presentation in all tasks. Slow response times were slower than 900 ms after stimulus presentation in the picture naming tasks and slower than 850 ms after stimulus presentation in the nonword reading task.

responses and trials with responses that consisted of too many syllables were excluded from the analysis (lemma retrieval: 13.5%; lexeme retrieval: 13%; phonological and phonetic encoding: 2.5%). The reason for the exclusion is that missing responses do not reveal whether the participant was processing the stimulus. For responses that consist of more syllables than the target response, the timing of the stages may have been different. Word length, for example, is known to affect the duration of phonological encoding. The average response time was computed over all accepted trials per subject group. In the NBDs, trials exceeding the average response time by 1.4 standard deviations were excluded. In the individuals with aphasia, the standard deviation of the average response time was larger than for the NBDs. Therefore, trials were disregarded when exceeding the average response time by 1 standard deviation.

EEG data

EEGLAB (Delorme & Makeig, 2004) as an extension to MATLAB (The MathWorks, 2015a) was used to preprocess the EEG data. After re-referencing to the average reference of the mastoids, the data were filtered with a 50 Hz notch filter to remove electricity noise and band-pass filtered from 0.2 to 30 Hz. Then, the data were resampled to 128 Hz. Independent components analysis on all channels was used for artifact detection. Artifact components, such as eye blinks, were removed through visual inspection. Also, the effect of component removal on the data was visually inspected. The continuous data were segmented per trial from 200 ms until 5 seconds after stimulus onset. A baseline correction was applied over the data epochs, using the 200 ms before stimulus onset as a baseline. Then, the events of disregarded trials were removed. To study the time window from the stimulus onset until the response onset, both stimulus-locked analyses, in which the time window after stimulus onset is analyzed, and response-locked analyses, in which the backwards time window before the response onset is analyzed, were carried out. For the stimulus-locked analysis, the data epochs were segmented from stimulus onset until one sampling point (8 ms) after the earliest response time. This one extra sampling point was removed before the analysis. The start of the response-locked analysis was determined by subtracting the stimulus-locked time window from the response onset. For the statistical analysis, accepted trials were coded into two conditions on the lemma retrieval task and into three conditions for the other tasks to account for the ordinal scale of the variables specified below. These data were exported from EEGLAB into the format used in FieldTrip (Oostenveld, Fries, Maris, & Van Schoffelen, 2011), which was used for the statistical analysis. Finally, the structure of the data files was prepared for a cluster-based permutation analysis (Maris & Oostenveld, 2007).

In every analysis, 5000 permutations were computed. The Monte Carlo method was used to compute significance probability. A family-wise error rate with an α of 0.025 was used to correct for the multiple comparison problem. A 2-sided paired samples t-test was used to test for the cumulative semantic interference effect, the AoA effect, the nonword length in phonemes effect and the syllable frequency effect in the group of individuals with a PED and in the group of individuals with AoS. The cumulative semantic interference effect was tested by comparing pictures presented at the fifth ordinal position to those presented at the first ordinal position. To test for the AoA effect, pictures of words with an AoA of around 6 and 7 years were compared to those with an AoA of around 5 years. The nonword length in phonemes effect was tested by comparing nonwords with a length of 5 and 6 phonemes to those with 4 phonemes. To test for a syllable frequency effect, nonwords with moderate and low syllable frequency were compared to those with high syllable frequency.

The group of individuals with a PED and the group of individuals with AoS were compared to the matched NBDs using a 2-sided independent samples t-test ($\alpha = 0.025$). Also, a 2-sided independent samples t-test ($\alpha = 0.025$) was used to compare the difference between the group of individuals with a PED and the matched NBDs to the difference between the group of individuals with AoS and the matched NBDs. To ensure that differences between the groups were tested at the targeted stage, the groups were compared on the conditions with the highest processing demands for that stage. This means that pictures that were presented at the fifth ordinal position were used for the lemma retrieval stage and pictures of words with an AoA of around 6 and 7 years were used for the lexeme retrieval stage. Nonwords consisting of 5 and 6 phonemes were used for the phonological encoding stage and nonwords with moderate and low syllable frequency were used for the phonetic encoding stage. In the first analysis of every experiment, the entire time window from stimulus onset until 100 ms before response onset was tested. Thus, both stimulus-locked and response-locked effects were studied in this time window. When an effect was revealed in the sampling points of this large time window, a smaller time window around the effect was tested once, so a more specific timing of the effect could be reported. An effect was defined as a cluster of at least 5 neighboring electrodes that was observed in one or more consecutive sampling points. The smaller time window was tested on all sampling points of the effect. Only significant effects will be reported in the results section and full details are provided in Appendices 10, 11 and 12.

4.3 Results

4.3.1 Behavioral results

Accuracy

Individual accuracy scores for the aphasic participants on all tasks are provided in Appendix 9. Neither group of individuals with aphasia showed an effect of cumulative semantic interference on the accuracy (PED: $F(1,518)=1.45$, $p = .23$, AoS: $F(1,548)=1.65$, $p = .199$). Only the individuals with AoS showed effects of AoA (PED: $F(1,13)=0.02$, $p = .884$, AoS: $F(1,1158)=7.01$, $p = .008$), nonword length in phonemes (PED: $F(1,260)=3.86$, $p = .050$, AoS: $F(1,1056)=19.98$, $p < .001$) and spoken syllable frequency (PED: $F(1,671)=2.92$, $p = .088$, AoS: F(1,1437)=11.02, p < .001) on the accuracy. Lower accuracy was observed on items with a later AoA, on items with a higher number of phonemes and on items with lower syllable frequency.

Both groups of aphasic speakers produced more errors than their matched NBDs on the picture naming paradigms used to track lemma retrieval (PED: F(1,1248)=179.1, p < .001, AoS: F(1,2748)=365.5, p < .001) and lexeme retrieval (PED: F(1,1398)=202.4, p < .001, AoS: F(1,3078)=496.4, p < .001). Both groups of individuals with aphasia also had lower accuracy than NBDs on the nonword reading task used to track phonological and phonetic encoding (PED: F(1,1398)=457.9, p < .001, AoS: F(1,3078)=1933, p < .001). Individuals with AoS had lower accuracy than individuals with a PED on the nonword reading task (F(1,2238)=36.78, p < .001). Group level accuracy data for both groups of aphasic speakers and their matched NBDs are provided in Table 4.1.

Table 4.1: Accuracy in percentages for the aphasic individuals with a PED, the individuals with AoS and their matched NBDs on all tasks. Mean accuracy (M), standard deviations (SD) and ranges (RNG) are reported as M (*SD*, RNG).

Task	PED	NBDs	AoS	NBDs
Picture naming: lemma retrieval	56 (*32.8*, 16.8-86.4)	87.8 (*3.2*, 84-92)	57.4 (*23.5*, 14.4-85.6)	87.9 (*6.5*, 76.8-96.8)
Picture naming: lexeme retrieval	56.3 (*38.6*, 6.4-90.7)	88.1 (*5.1*, 82.8-96.4)	55.1 (*20.8*, 22.9-75.7)	88.6 (*6.4*, 77.2-97.9)
Nonword reading: phonological and phonetic encoding	50.9 (*44.3*, 0-95)	95 (*3.2*, 90.7-99.3)	37.3 (*23.3*, 0-74.3)	95.9 (*3.4*, 90-100)

Response time

A cumulative semantic interference effect was observed on the response time in the individuals with AoS (F(1,348)=12.76, p < .001) on the picture naming task targeting lemma retrieval. Increased response times were found for items that were presented at the fifth ordinal position compared to items that were presented at the first ordinal position within the same category. No such effect was found in the individuals with a PED (F(1,120)=0.24, p = .629). Neither group of individuals with aphasia showed an effect of AoA (PED: F(1,366)=1.02, p = .312, AoS: F(1,955)=3.44, p = .064), nonword length in phonemes (PED: F(1,564)=3.64, p = .056, AoS: F(1,1036)=3.21, p = .195) or spoken syllable frequency (PED: F(1,564)=0.48, p = .073, AoS: F(1,1036)=0.26, p = .608) on the response time.

The response times of both groups of aphasic speakers were slower than for their matched NBDs on the lemma retrieval task (PED vs. NBDs: F(1,761)=129.4, p < .001, AoS vs. NBDs: F(1,1866)=304.9, p < .001) and on the lexeme retrieval task (PED vs NBDs: F(1,757)=136.5, p < .001, AoS vs NBDs: F(1,1839)=367.2, p < .001). On the nonword reading task, individuals with aphasia also required more time to respond than NBDs (PED vs. NBDs: F(1,877)=662.9, p < .001, AoS vs. NBDs: F(1,1837)=570.2, p < .001). On this task, shorter response times were found for individuals with AoS than for individuals with a PED ($F(1,1603)=33.28$, $p < .001$). The response times at the group level for the aphasic speakers and the NBDs are provided in Table 4.2.

Table 4.2: Response times after stimulus presentation with their mean (*standard deviation*, range) in ms for the individuals with a PED, the individuals with AoS and their matched NBDs on all tasks.

Task	PED	NBDs	AoS	NBDs
Picture naming: lemma retrieval	1194.3 (*278.2*, 629-1781)	996.5 (*202*, 614-1453)	1175 (*284.1*, 614-1781)	977.4 (*202.4*, 604-1453)
Picture naming: lexeme retrieval	1171.5 (*271*, 652-1767)	974.3 (*193.5*, 631-1436)	1166 (*284.1*, 629-1781)	949 (*197.4*, 628-1436)
Nonword reading: phonological and phonetic encoding	1120 (*244.8*, 681-1736)	758 (*121.2*, 511-965)	993.6 (*295.3*, 518-1736)	736.9 (*128*, 505-965)

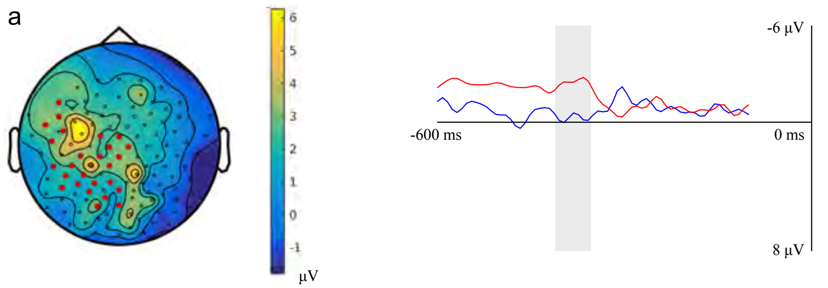
4.3.2 EEG results

First, EEG results will be presented to identify the time windows of the cumulative semantic interference effect, the AoA effect, the nonword length in phonemes effect and the syllable frequency effect for each task in the individuals with a PED and then in the individuals with AoS. Second, differences between both groups of individuals with aphasia and their matched NBDs will be reported. Finally, differences between individuals with a PED and matched NBDs will be compared to differences between individuals with AoS and their matched NBDs. When effects were found in multiple time windows for one analysis, the time window of the effect with the largest duration is shown in the figure. The statistical details of the EEG results are provided in Appendix 10 (individuals with a PED), Appendix 11 (individuals with AoS) and Appendix 12 (comparison of the aphasic speakers to their matched NBDs and indirect comparison of the two groups of aphasic speakers). Only statistical details for clusters with significant effects will be reported.

Individuals with a PED

The cluster-based permutation analysis showed no cumulative semantic interference effect on the EEG data recorded during the picture naming task which was used to track *lemma retrieval* in individuals with a PED. Testing for an AoA-effect in the EEG data of the picture naming task used to track *lexeme retrieval*, the comparison of items with an AoA of around 5 years to those with an AoA of around 6 years revealed a short stimulus-locked effect from 140 to 155 ms after stimulus presentation ($p < .001$). Also, response-locked effects from 535 to 445 ms and from 410 to 355 ms before response onset ($p < .001$; $p < .001$) were found for this comparison. The scalp distribution and the waveform of the effect in the time window from 410 to 355 ms before response onset are shown in Figure 4.2a. In the left panel, the scalp distribution shows that the electrodes included in cluster, which are marked red, were most pronounced over the left hemisphere. In the right panel, in the highlighted time window of the effect from 410 to 355 ms before response onset, the waveform for items with an AoA of around 6 years was more negative than the waveform for items with an AoA of around 5 years. Also, AoA-effects were found for the comparison of items with an AoA of around 5 years to items with an AoA of around 7 years in the time windows from 475 to 530 ms and from 545 to 570 ms after stimulus presentation ($p < .001$; $p < .001$) as well as from 570 to 550 ms before response onset ($p < .001$). The scalp distribution and the waveforms of the effect in the time window from 475 to 530 ms are shown in Figure 4.2b. The scalp distribution shows that the effect was most pronounced over frontal and central electrodes. The waveform of items with an AoA of around 7 years is more positive than the waveform of items with an AoA of around 5 years in the time window of the effect.

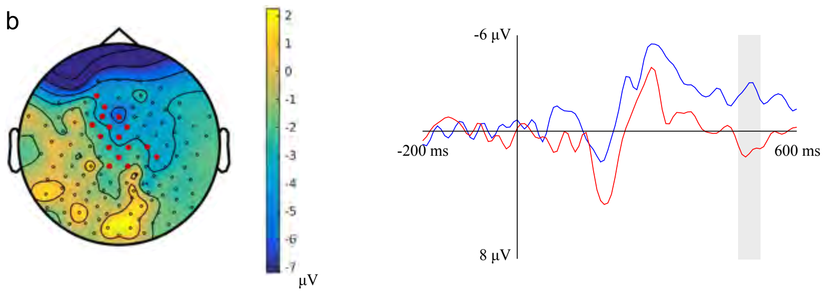
In the nonword reading EEG data, no effect of nonword length in phonemes was found that could be used to track the stage of *phonological encoding* in the individuals with a PED. To track the stage of *phonetic encoding*, a syllable frequency effect from 385 to 170 ms before response onset was found for the comparison of items with high and moderate syllable frequency ($p < .001$). The scalp distribution in Figure 4.3a shows that the effect was most pronounced over bilateral frontal and central electrodes. The waveform of the moderate syllable frequency condition was more negative than the waveform of the high syllable frequency condition in the time window of the effect. Also, an effect of syllable frequency from 410 to 500 ms after stimulus presentation was found for the comparison between items with high and low syllable frequency ($p < .001$). In that time window in Figure 4.3b, the waveform of the nonwords with low syllable frequency was more positive than the waveform of items with high syllable frequency. The scalp distribution shows that the effect was most pronounced over right frontal and central electrodes.



Participant group	Phon. enc. dis.
Difference	AoA ca. 5 vs. ca. 6 years
Timing	-410 - -355 ms pre-response onset

grand averages over left central and posterior electrodes included in the cluster

AoA ca. 5 years = blue
AoA ca. 6 years = red



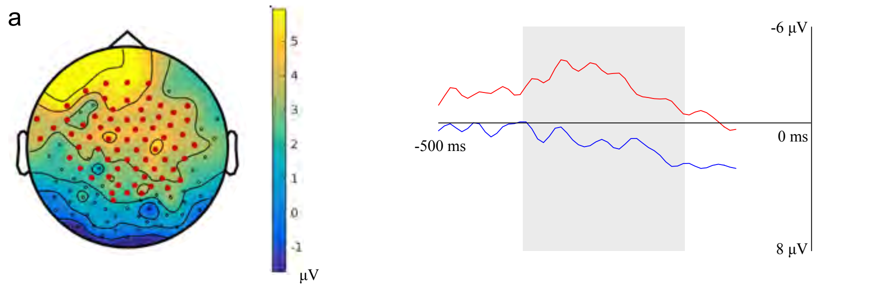
Participant group	Phon. enc. dis.
Difference	AoA ca. 5 vs. ca. 7 years
Timing	475 - 530 ms post-stimulus onset

grand averages over frontal and central electrodes included in the cluster

AoA ca. 5 years = blue
AoA ca. 7 years = red

Figure 4.2a: Left: cluster related to the difference between items with an AoA of 5 and 6 years identified in the response-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with an AoA of 5 (in blue) and 6 years (in red) over the left central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

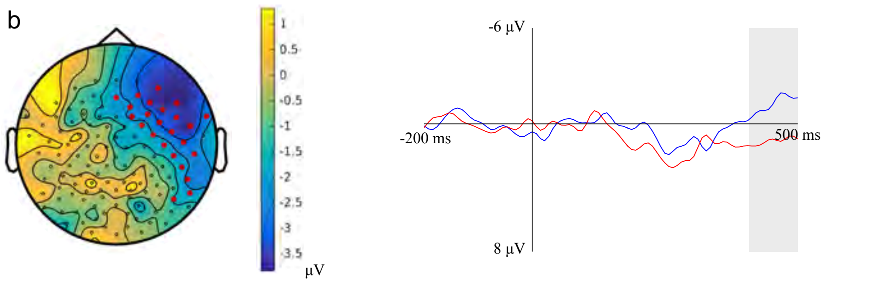
Figure 2.4b: Left: cluster related to the difference between items with an AoA of 5 and 7 years identified in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with an AoA of 5 (in blue) and 7 years (in red) over the frontal and central electrodes included in the cluster. The time window of the effect is highlighted.



Participant group	Phon. enc. dis.
Difference	High vs. moderate frequency
Timing	-385 - -170 ms pre-response onset

grand averages over frontal and central electrodes included in the cluster

High frequency = blue
Moderate frequency = red



Participant group	Phon. enc. dis.
Difference	High vs. low frequency
Timing	410 - 500 ms post-stimulus onset

grand averages over right frontal and central electrodes included in the cluster

High frequency = blue
Low frequency = red

4

Figure 4.3a: Left: cluster related to the difference between nonwords with high and moderate syllable frequency identified in the response-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for nonwords with high (in blue) and moderate syllable frequency (in red) over bilateral frontal and central electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.3b: Left: cluster related to the difference between nonwords with high and low syllable frequency identified in the stimulus-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for nonwords with high (in blue) and low syllable frequency (in red) over right frontal and central electrodes included in the cluster. The time window of the effect is highlighted.

Individuals with AoS

In the EEG data of the individuals with AoS, the cluster-based permutation analysis revealed no effects of cumulative semantic interference in the picture naming task used to track *lemma retrieval*. In the picture naming task targeting *lexeme retrieval*, an AoA effect was found for the comparison of items with an AoA of around 5 years to items with an AoA of around 6 years from 225 to 335 ms after stimulus onset (p =.012). Figure 4.4 shows that the effect was most pronounced over central electrodes. During the time window of the effect, the waveform of items with an AoA of around 6 years was more negative than the waveform of items with an AoA of around 5 years.

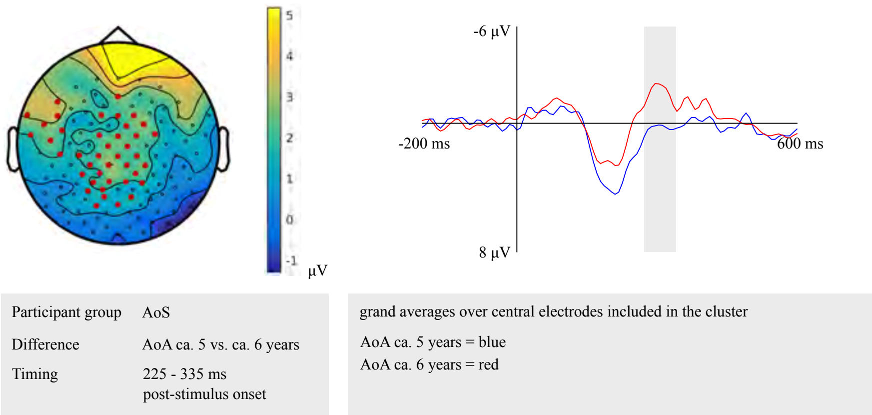
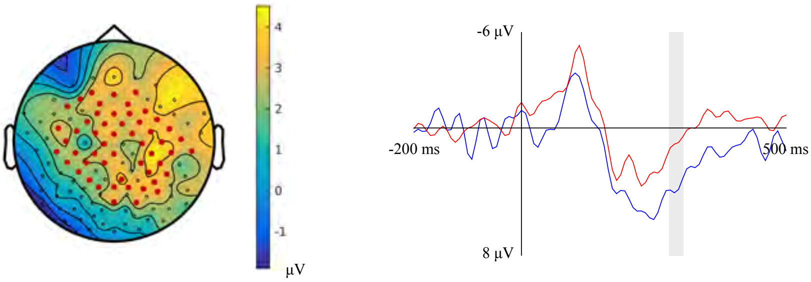


Figure 4.4: Left: cluster related to the difference between items with an AoA of 5 and 6 years identified in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for items with an AoA of 5 (in blue) and 6 years (in red) over the central electrodes included in the cluster. The time window of the effect is highlighted.

Tracking *phonological encoding*, an effect of nonword length in 4 compared to 5 phonemes was found from 280 to 305 ms after stimulus presentation (p = .006). Figure 4.5 shows that the effect was recorded over a widespread area of the scalp. The waveform of items with 5 phonemes was more negative than the waveform of items with 4 phonemes in the time domain of the effect. No effects of syllable frequency were found in the nonword reading task used to target *phonetic encoding*.



Participant group	AoS
Difference	Length 4 vs. 5 phonemes
Timing	280 - 305 ms post-stimulus onset

grand averages over frontal and central electrodes included in the cluster

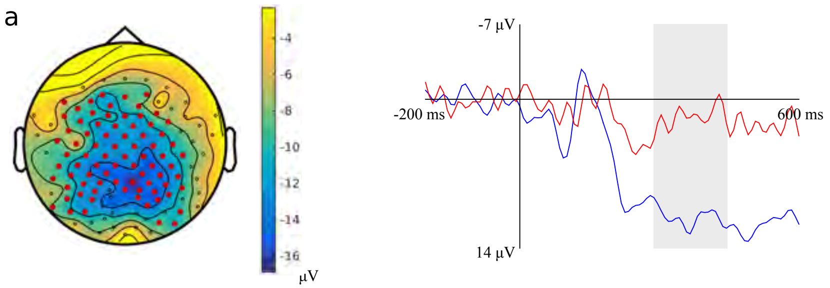
Length 4 phonemes = blue
Length 5 phonemes = red

Figure 4.5: Left: cluster related to the difference between nonwords consisting of 4 and 5 phonemes identified in the stimulus-locked analysis of the phonological encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for nonwords consisting of 4 (in blue) and 5 phonemes (in red) over bilateral frontal and central electrodes included in the cluster. The time window of the effect is highlighted.

Differences between individuals with a PED and matched NBDs

In the EEG data on items in fifth ordinal position on the picture naming task targeting *lemma retrieval*, differences between individuals with a PED and matched NBDs were found from 130 to 175 ms and from 290 to 445 ms after stimulus presentation ($p < .001$; $p < .001$). Figure 4.6a shows the effect in the time window from 290 to 445 ms, which was recorded over bilateral frontal, central and posterior electrodes. The waveform of the individuals with a PED remained near 0 µV in the time window of the effect, while the waveform of the NBDs showed a positivity. Also, differences between the participant groups were found from 600 to 575 ms, from 565 to 500 ms and from 190 to 165 ms before response onset ($p < .001$; $p = .006$; $p = .006$). The effect that was observed from 565 to 500 ms before response onset was most pronounced over right posterior electrodes, as shown in Figure 4.6b. Again, the waveform of the NBDs showed a positivity in the time window of the effect, while this positivity was absent in the individuals with a PED.

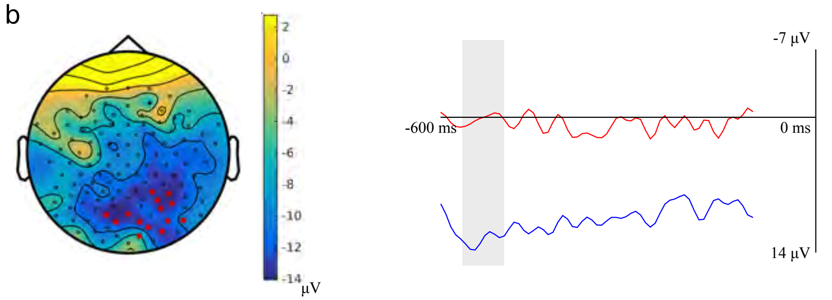
On the picture naming task targeting *lexeme retrieval*, differences between individuals with a PED and NBDs were found on items with an AoA of around 6 years from 295 to 520 ms after stimulus presentation ($p = .005$) and from 600 to 335 ms before response onset ($p < .001$). The stimulus-locked effect was most pronounced over bilateral posterior electrodes (see Figure 4.7a). The waveform of the individuals with a PED was around 0 µV, while a positivity was observed for the NBDs in the time window of the effect. The response-locked effect was recorded over bilateral central and posterior electrodes (see Figure 4.7b). The waveform in this time window of the NBDs was more positive than the waveform of the individuals with a PED. For items with an AoA of around 7 years, differences between participant groups were found from 320 to 500 ms after stimulus presentation (p = .002) and from 390 to 290 ms before response onset (p = .003).



Difference	Phon. enc. dis. vs NBD
Condition	5th item in ordinal position
Timing	290 - 445 ms post-stimulus onset

grand averages over frontal, central and posterior electrodes included in the cluster

NBD = blue
Phon. enc. dis. = red



Difference	Phon. enc. dis. vs NBD
Condition	5th item in ordinal position
Timing	-565 - -500 ms pre-response onset

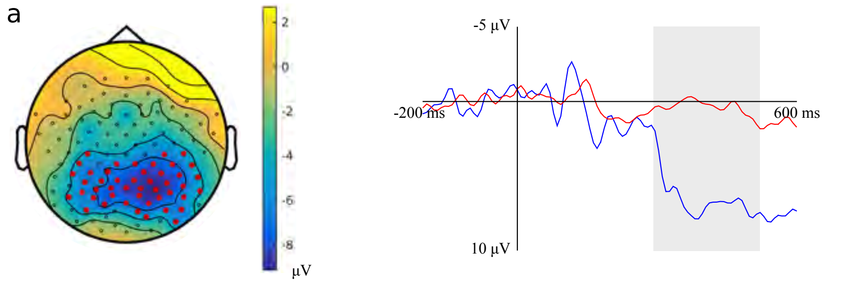
grand averages over right posterior electrodes included in the cluster

NBD = blue

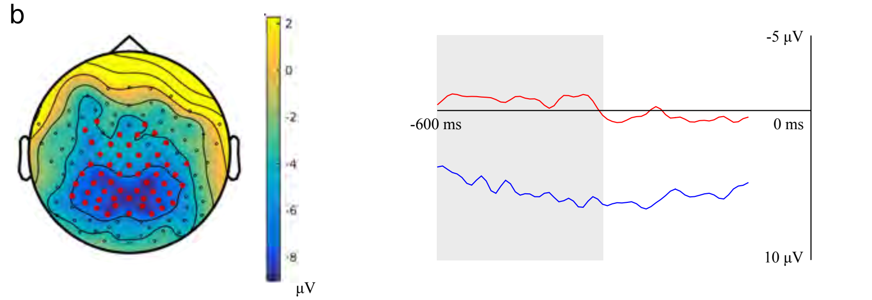
Phon. enc. dis. = red

Figure 4.6a: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the stimulus-locked analysis of the lemma retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.6b: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the response-locked analysis of the lemma retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over right posterior electrodes included in the cluster. The time window of the effect is highlighted.



Difference	Phon. enc. dis. vs NBD	grand averages over posterior electrodes included in the cluster
Condition	AoA ca. 6 years	NBD = blue
Timing	295 - 520 ms post-stimulus onset	Phon. enc. dis. = red



Difference	Phon. enc. dis. vs NBD	grand averages over central and posterior electrodes included in the cluster
Condition	AoA ca. 6 years	NBD = blue
Timing	-600 - -335 ms pre-response onset	Phon. enc. dis. = red

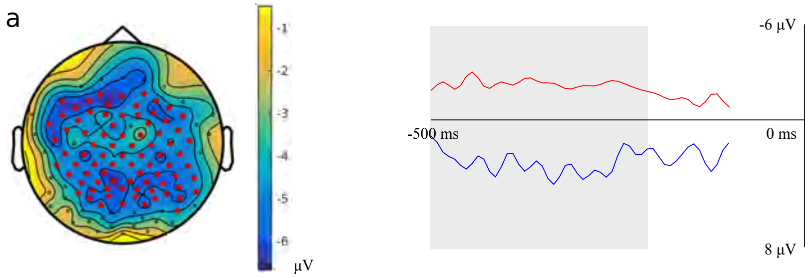
Figure 4.7a: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral posterior electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.7b: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the response-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Regarding *phonological encoding* tracked using the nonword reading task, individuals with a PED differed from matched NBDs on nonwords with a length of 5 phonemes from 500 to 210 ms before response onset ($p < .001$) and on nonwords consisting of 6 phonemes from

130 to 180 ms after stimulus onset (p = .006). The electrodes included in the cluster of the response-locked effect were widespread over the scalp, as shown in Figure 4.8a. While a slow negative waveform was observed in the individuals with a PED, a slow positive waveform was observed in the NBDs. The stimulus-locked effect was found over bilateral frontal and central electrodes as shown in Figure 4.8b. The waveforms in the time window of the effect showed a positive peak in the NBDs, which was attenuated and observed after the time window of the effect in the individuals with a PED.

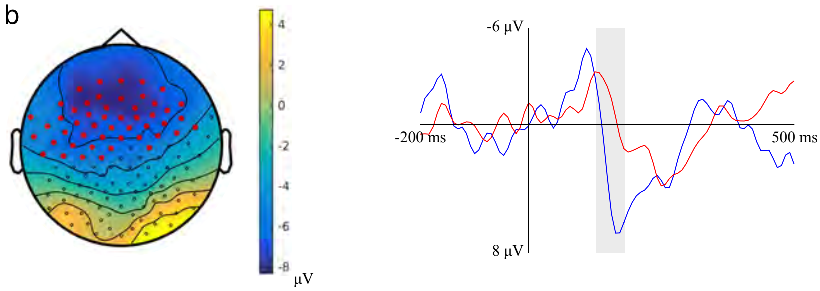
Differences between individuals with a PED and matched NBDs were found from 390 to 500 ms after stimulus presentation (p = .004) and from 355 to 325 ms before response onset (p = .011) on items with moderate syllable frequency when tracking *phonetic encoding*. Both effects were observed over bilateral frontal, central and posterior electrodes. The waveform of the individuals with a PED was more negative than the waveform of the NBDs in the time window of the stimulus-locked effect shown in Figure 4.9a. This was also the case for the response-locked effect shown in Figure 4.9b. For items with low syllable frequency, differences between the participant groups were found from 130 to 190 ms after stimulus presentation (p = .004).



Difference	Phon. enc. dis. vs NBD
Condition	5 phonemes
Timing	-500 - -210 ms pre-response onset

grand averages over frontal, central and posterior electrodes included in the cluster

NBD = blue
Phon. enc. dis. = red



Difference	Phon. enc. dis. vs NBD
Condition	6 phonemes
Timing	130 - 180 ms post-stimulus onset

grand averages over frontal and central electrodes included in the cluster

NBD = blue

Phon. enc. dis. = red

Figure 4.8a: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the response-locked analysis of the phonological encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.8b: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the stimulus-locked analysis of the phonological encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral frontal and central electrodes included in the cluster. The time window of the effect is highlighted.

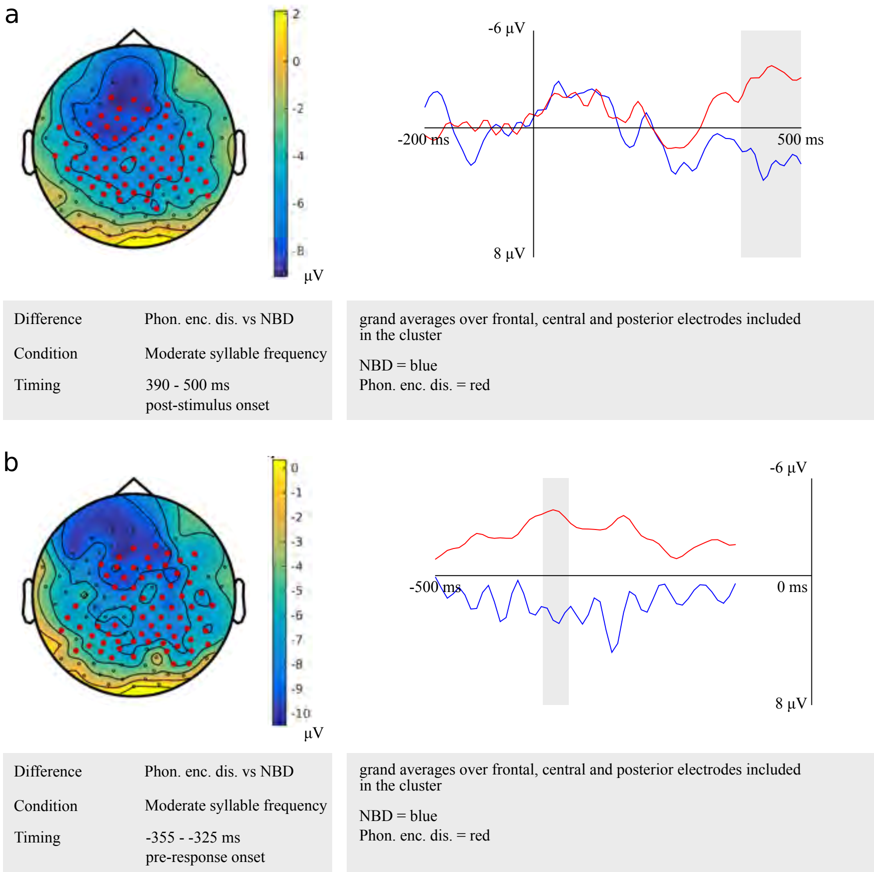


Figure 4.9a: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the stimulus-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.9b: Left: cluster related to the difference between individuals with a phonological encoding disorder and NBDs identified in the response-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with a PED (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Differences between individuals with AoS and matched NBDs

No differences between individuals with AoS and matched NBDs were found for items that were presented at fifth ordinal position on the picture naming task targeting *lemma retrieval*.

On the picture naming task used to track *lexeme retrieval*, differences between these participant groups were found from 360 to 525 ms after stimulus presentation (p = .022) on items with an AoA of around 6 years. The effect was most pronounced over bilateral posterior electrodes, as shown in Figure 4.10. In the time window of the effect, the waveform of the individuals with AoS was close to 0 µV, while the waveform of the NBDs showed a positivity.

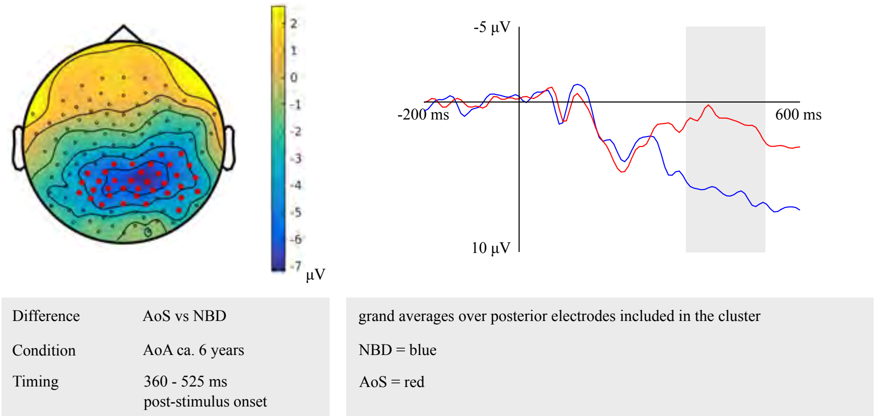
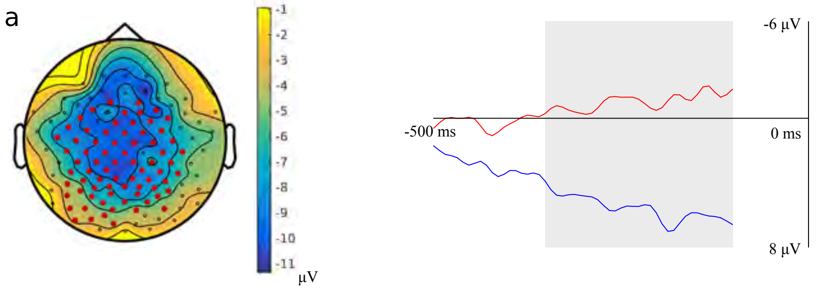


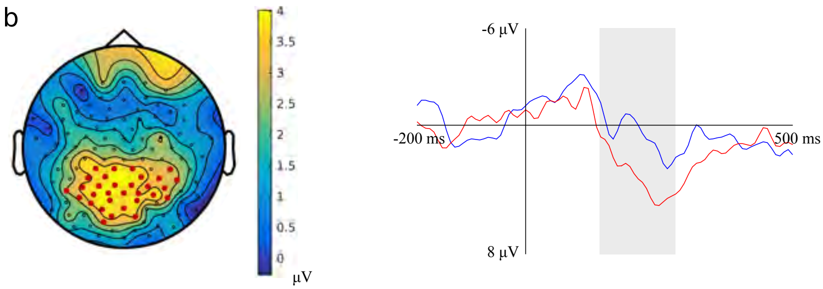
Figure 4.10: Left: cluster related to the difference between individuals with AoS and NBDs identified in the stimulus-locked analysis of the lexeme retrieval task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with AoS (in red) over bilateral posterior electrodes included in the cluster. The time window of the effect is highlighted.

4

For nonwords with a length of 5 phonemes on the nonword reading task tracking *phonological encoding*, individuals with AoS differed from matched NBDs from 195 to 235 ms after stimulus presentation (p = .018) and from 350 to 100 ms before response onset (p = .006). The response-locked effect was observed over frontal, central and posterior electrodes, as shown in Figure 4.11a. In the time window of the effect, the waveform of the individuals with AoS showed a slow negativity, while the waveform of the NBDs showed a positivity. For nonwords consisting of 6 phonemes, differences between the participant groups were found from 140 to 280 ms after stimulus presentation (p = .022). The effect was most pronounced over posterior electrodes, as shown in Figure 4.11b. The waveform of the NBDs showed a negative peak which was larger than the negative peak in the waveform of the individuals with AoS in the time window of the effect.



Difference	AoS vs NBD	grand averages over frontal, central and posterior electrodes included in the cluster
Condition	5 phonemes	NBD = blue
Timing	-350 - -100 ms pre-response onset	AoS = red

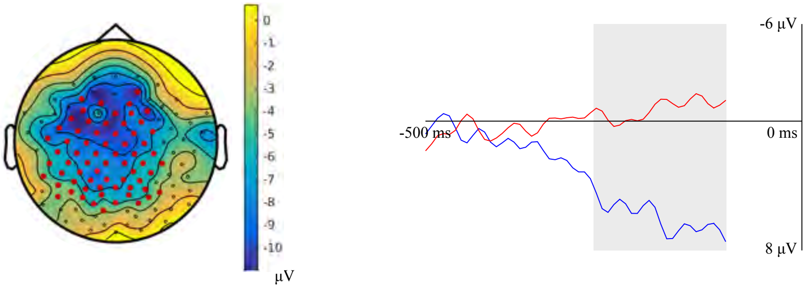


Difference	AoS vs NBD	grand averages over posterior electrodes included in the cluster
Condition	6 phonemes	NBD = blue
Timing	140 - 280 ms post-stimulus onset	AoS = red

Figure 4.11a: Left: cluster related to the difference between individuals with AoS and NBDs identified in the response-locked analysis of the phonological encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with AoS (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Figure 4.11b: Left: cluster related to the difference between individuals with AoS and NBDs identified in the stimulus-locked analysis of the phonological encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with AoS (in red) over bilateral posterior electrodes included in the cluster. The time window of the effect is highlighted.

From 275 to 100 ms before response onset (p = .016), individuals with AoS differed from matched NBDs on nonwords with moderate syllable frequency in the reading task used to track *phonetic encoding*. The effect was recorded at frontal, central and posterior electrodes as shown in Figure 4.12. A slow negative waveform was observed around 0 μV in the individuals with AoS, while the waveform of the NBDs showed a positivity.



Difference	AoS vs NBD	grand averages over frontal, central and posterior electrodes included in the cluster
Condition	Moderate syllable frequency	NBD = blue
Timing	-275 - -100 ms pre-response onset	AoS = red

Figure 4.12: Left: cluster related to the difference between individuals with AoS and NBDs identified in the response-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for NBDs (in blue) and individuals with AoS (in red) over bilateral frontal, central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

Differences between individuals with a PED and individuals with AoS

The comparison of the difference between individuals with a PED and their matched NBDs and the difference between individuals with AoS and their matched NBDs revealed a difference only on nonwords with a moderate syllable frequency used to track *phonetic encoding* in the nonword reading task from 430 to 500 ms after stimulus presentation (p = .013). The effect was most pronounced over bilateral central and posterior electrodes, which is shown in Figure 4.13. The waveforms had a comparable morphology. However, the waveform of the difference between the individuals with AoS and the NBDs remained closer to 0 μV than the waveform of the difference between the individuals with a PED and the NBDs, which showed a negativity.

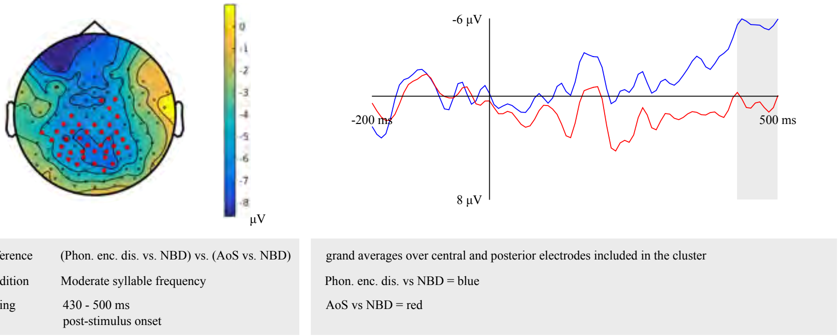


Figure 4.13: Left: cluster related to the difference between the difference between individuals with a PED and NBDs and the difference between individuals with AoS and NBDs identified in the stimulus-locked analysis of the phonetic encoding task. Electrodes included in the cluster are marked in red.
Right: waveforms of the grand averages for the difference between individuals with a PED and NBDs (in blue) and the difference between individuals with AoS and NBDs (in red) over bilateral central and posterior electrodes included in the cluster. The time window of the effect is highlighted.

4.4 Discussion

The aim of the study was to test whether our EEG protocol could be used to distinguish individuals with aphasia and a PED from individuals with aphasia and AoS. First, we asked whether all speech production stages could be identified in the two groups of individuals with aphasia by using EEG. Not all stages were identified, but lexeme retrieval was identified in both groups, phonological encoding was identified in the individuals with AoS and phonetic encoding was identified in the individuals with a PED. These findings will be discussed in Section 4.4.1. Second, the aphasic speakers were compared to matched NBDs on all four speech production stages. The research question was at which stages the two groups of individuals with aphasia differed from matched NBDs. Individuals with a PED differed at all stages from their matched NBDs and individuals with AoS differed from their matched NBDs at the lexeme retrieval stage, the phonological encoding stage and at the phonetic encoding stage. This will be discussed in Section 4.4.2. Third, the difference between individuals with a PED and their matched NBDs was compared to the difference between individuals with AoS and their matched NBDs. The research question was at which stage the two groups of individuals with aphasia differed from one another, which found to be at the phonetic encoding stage. This finding will be discussed in Section 4.4.3. In every part of the Discussion, the results will be discussed in the order of appearance of the stages in the process of spoken word production. Finally, we will address the question whether the EEG protocol can be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS.

4.4.1 Identification of speech production stages in individuals with aphasia

An overview of the timing of the identified speech production stages in the NBDs, the individuals with a PED and the individuals with AoS in the EEG data is provided in Figure 4.14.

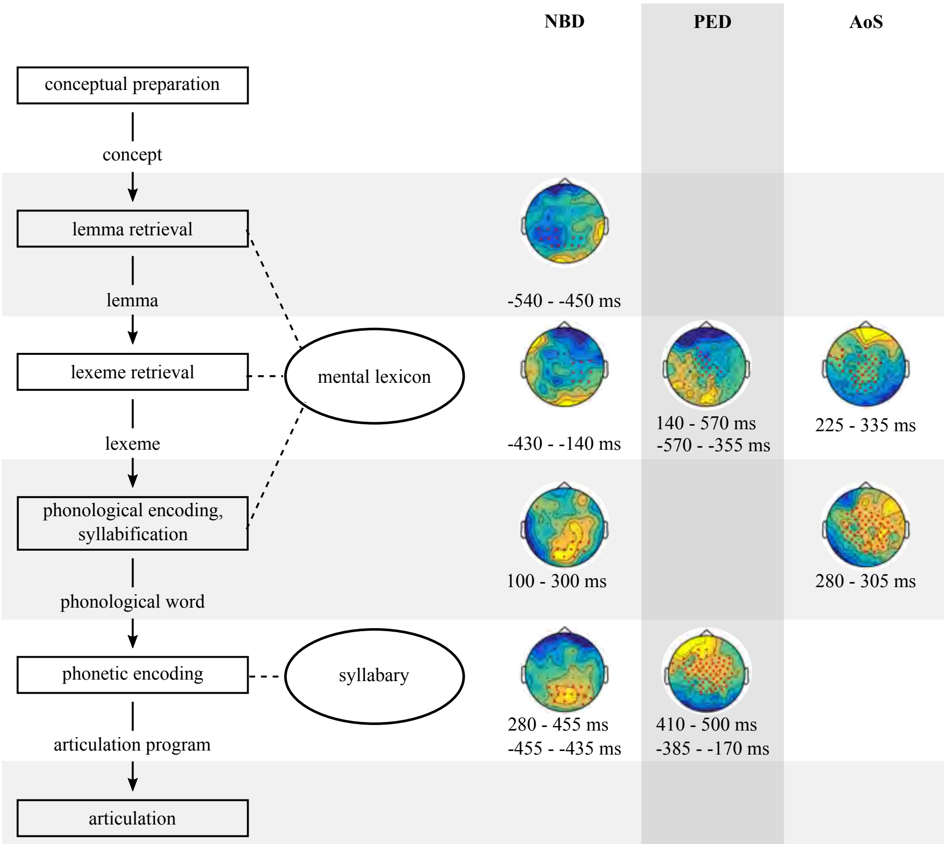


Figure 4.14: Timing and scalp distribution of the speech production stages identified in the EEG data of the NBDs (the older adults from Chapter 3), the individuals with a PED and the individuals with AoS.

4

Lemma and lexeme retrieval

It was hypothesized that the cumulative semantic interference effect and the AoA effect would be reflected in the accuracy data, in the response time data and in the EEG data of the individuals with aphasia recorded during the picture naming task targeting lemma and lexeme retrieval. The cumulative semantic interference effect, which was used to track *lemma retrieval*, was observed only in the response time data of the individuals with AoS. The effect was not identified in the EEG data. This indicates that the EEG response reflecting the (behavioural) cumulative semantic interference effect varied between participants with AoS, so no cluster could be identified in the cluster-based permutation analysis.

The AoA effect, which was used to target *lexeme retrieval*, was only reflected in the accuracy data of the individuals with AoS. A comparable pattern was observed in the accuracy data of the individuals with a PED, even though it was not significant. The group of individuals with a PED was smaller than the group of individuals with AoS, so the offline measures were possibly not sensitive enough to find an effect of AoA in the PED group. In both groups of individuals with aphasia, an AoA effect was observed in the EEG data. Hence, there was a discrepancy between the online and offline outcomes in the individuals with a PED. Such discrepancy was previously reported in individuals with aphasia (Dickey, Choy, & Thompson, 2007). Compared to the timing of the response-locked AoA effect in the older neurologically healthy adults reported in Den Hollander et al. (2019), an increased duration between the response-locked AoA effect and the response was observed in the individuals with a PED. This does not mean that the effect took place earlier in the individuals with a PED, because their response times were slower than the response times of the NBDs. Individuals with a PED probably required more time for phonological encoding, which increased the duration of that stage compared to the NBDs. This had an impact on the timing of the lexeme retrieval stage preceding the phonological encoding stage.

Phonological and phonetic encoding

A nonword length in phonemes effect and a syllable frequency effect were predicted for in the accuracy data, in the response time data and in the EEG data of the individuals with aphasia recorded during the nonword reading task targeting phonological and phonetic encoding. Effects of nonword length in phonemes and syllable frequency were found only in the accuracy data of the individuals with AoS. In the individuals with a PED, comparable patterns were found, which were nearly significant. The nonword reading task may not have been sensitive enough to detect behavioural effects in the group of individuals with a PED, because the group was smaller than the group of individuals with AoS. The EEG data revealed an effect of nonword length in phonemes used to target *phonological encoding* in the individuals with AoS, but not in the individuals with a PED. The onset of the stimulus-locked effect of nonword length in phonemes was 180 ms later in the individuals with AoS than in the older neurologically healthy adults reported in Den Hollander et al. (2019), but the offset was only 5 ms later. This shows that the phonological encoding stage was delayed in the individuals with AoS compared to the NBDs. Interference from the phonetic encoding stage may have reduced the time window in which a common cluster was found.

An effect of syllable frequency, which was used to target *phonetic encoding*, was only found in the EEG data of the individuals with a PED. Hence, a discrepancy between online and offline measures was observed in both groups of individuals with aphasia (see: Dickey et al., 2007). The stimulus-locked effect started later in the individuals with a PED as compared to the older neurologically healthy adults reported in Den Hollander et al. (2019). As the stimulus-locked analysis was carried out up to 500 ms after stimulus onset to avoid noise that muscle activity from faster responses would have added to the EEG signal, we cannot conclude that the stimulus-locked effect was shorter than for the NBDs. The response-locked syllable frequency effect found in the individuals with a PED took place later and lasted longer than the response-locked effect of the older neurologically healthy adults reported in Den Hollander et al. (2019). A potential reason for the later onsets of the syllable frequency effect in individuals with a PED was that they required more time during the phonological encoding stage than the NBDs.

The EEG response to the (behavioural) syllable frequency effect from the individuals with AoS was probably modulated by the severity of the AoS (e.g. Laganaro et al., 2009), which varied between these participants, so no cluster could be identified. The absence of an effect of syllable frequency in the EEG data of individuals with AoS suggests that the individuals with AoS could not activate the articulation plans. This is in line with Varley and Whiteside (2001), Varley et al. (2006) and Whiteside and Varley (1998). We assumed that the articulation plans were syllable-sized for the production of the nonwords used in this task, because the nonwords consisted of existing Dutch syllables. Effects of syllable frequency were found in the EEG data of the older neurologically healthy adults in Den Hollander et al. (2019) (Chapter 3), in the EEG data of the individuals with PED and in the accuracy of the individuals with AoS, which also supports the assumption of syllable-sized articulation plans. The production of nonwords with high syllable frequency was compared to the production of nonwords with moderate and low syllable frequency. If the articulation plans of high frequency syllables could not be activated, it would not make a difference whether the individuals with AoS produced a high, a moderate or a low frequency syllable, as the articulation plan for every syllable would be computed on demand. This led to a higher error rate in the individuals with AoS as compared to the individuals with a PED. The syllable frequency effect on the accuracy of the individuals with AoS suggests that they made more errors when computing articulation plans for nonwords with moderate and low syllable frequency as compared to nonwords with high syllable frequency. But, the number of items per condition to which individuals with AoS responded correctly does not necessarily relate to the EEG data, in which correct and incorrect responses were analyzed. Aichert and Ziegler (2004) only found a syllable frequency effect on the accuracy in individuals with AoS in a word repetition task for words comprising higher frequency syllables than those in the nonwords used in the reading task of the current study. Syllable frequency possibly had a larger impact on the accuracy in the production of nonwords than in the production of words in individuals with AoS. As all the syllables used in our nonwords were above mean syllable frequency for Dutch, the corresponding articulation plans should be stored. If the plans were retrieved incorrectly, as Aichert and Ziegler (2004) suggested is the case in individuals with AoS, the retrieval of high, moderate and low frequency syllables was equally impaired. This is what we found in the EEG data of the individuals with AoS in the current study, but not in the accuracy data of the individuals with AoS.

Not finding a statistically significant effect of syllable frequency in the EEG data of the individuals with AoS does not mean that syllable frequency had no impact on the EEG response at all. No effect of syllable frequency was observed in the EEG data of the individuals with AoS, whereas the syllable frequency effect was observed in the EEG data of the NBDs and the individuals with a PED. The EEG data of the NBDs and the individuals with AoS did not differ on the nonwords with low syllable frequency, but the EEG data did differ on nonwords with moderate syllable frequency. A similar pattern was observed in the comparison of the EEG data of the individuals with a PED and the NBDs: differences between these participant groups were observed in a much longer time window on nonwords with moderate syllable frequency than on nonwords with low syllable frequency. The syllable frequency effect with the longest duration was observed in the individuals with a PED, the effect was shorter in the NBDs and the smallest (and not significant) syllable frequency effect was identified in the individuals with AoS. Both Varley et al. (2006) and Aichert and Ziegler (2004) expect that syllable frequency effects can be observed in individuals with AoS, but only in the higher syllable frequency bounds. The fact that the EEG data of the individuals with AoS differed from the NBDs on nonwords with moderate syllable frequency, but not on nonwords with low syllable frequency, shows that there was an effect of syllable frequency in the higher syllable frequency bounds in the individuals with AoS, which fits with this tendency. However, the effect of syllable frequency was observed in the response time data of the NBDs, in the accuracy data of the individuals with AoS and in the EEG data of the NBDs and the individuals with a PED, but the effect was too small to be reflected in the EEG data of the individuals with AoS.

4.4.2 Differences between individuals with aphasia and matched NBDs

As hypothesized, individuals with aphasia had lower accuracy and slower response times than the NBDs on all tasks. Regardless of which stage was impaired in the individuals with aphasia, it impacted on their performance on the picture naming tasks and the nonword reading task. The timing of the differences between individuals with a PED and matched NBDs and the difference between individuals with AoS and matched NBDs per speech production stage observed in the EEG data is provided in Figure 4.15.

Lemma and lexeme retrieval

It was hypothesized that the individuals with aphasia differed from the NBDs at the lemma and lexeme retrieval stage, because the majority of individuals with aphasia had word finding difficulties. This hypothesis was supported by the findings of the current study. On the picture naming task targeting *lemma retrieval*, the stimulus-locked time windows of the difference between individuals with a PED and NBDs overlapped with the time windows in which Laganaro et al. (2009) found differences between individuals with aphasia and NBDs on a picture naming task. The response-locked effects cannot be compared as Laganaro et al. (2009) did not report these.

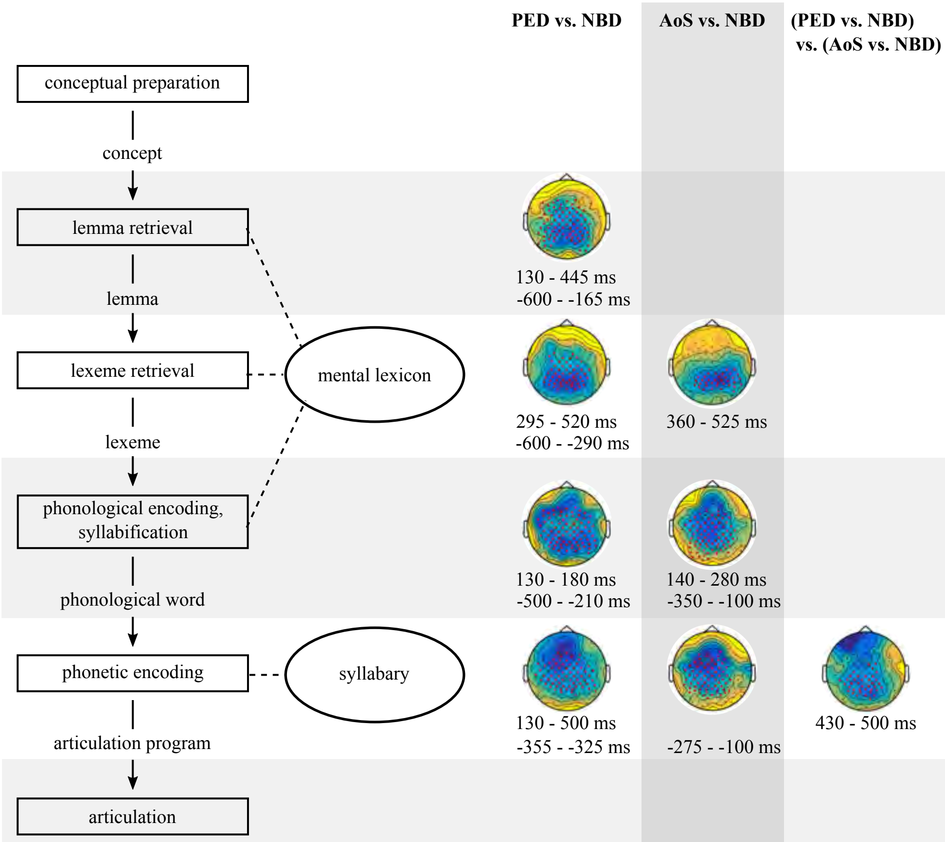


Figure 4.15: Timing and scalp distribution of the differences in the EEG data between individuals with a PED and matched NBDs and between individuals with AoS and matched NBDs as well as the difference between these differences identified per speech production stage.

On the picture naming task targeting *lexeme retrieval*, the time windows of the differences between individuals with a PED and NBDs largely overlapped with the time windows in which differences between individuals with AoS and NBDs were found. This also was the case on the picture naming task in the study by Laganaro et al. (2013). The time window of the difference between individuals with AoS and NBDs was similar to the time window in which individuals with a phonological disorder and individuals with AoS differed from NBDs on the picture naming task in the study by Laganaro et al. (2013), but the onset of the difference was 10 ms earlier in the present study. The timing of the differences between individuals with a PED and NBDs had a much earlier onset than the time window identified by Laganaro et al. (2013). The earlier onset can be explained by the fact that the words used in our protocol were shorter and more frequent than the words used by Laganaro et al. (2013).

The stimulus-locked effects in the EEG data of the picture naming tasks showed a positivity for the NBDs which was not observed in the individuals with aphasia. This suggests that the process that took place in the NBDs was weaker or not taking place in the same time window in the individuals with aphasia. The cumulative semantic interference effect and the AoA effect did not seem to modulate this positivity in the older neurologically healthy adults, because Den Hollander et al. (2019) have identified lemma and lexeme retrieval in response-locked time windows only. Although the NBDs in this study are a selection of the NBDs in the study by Den Hollander et al. (2019), results may differ, as the NBDs were divided into two groups in this study: one matching the aphasic speakers with PED and one matching the aphasic speakers with AoS.

Phonological encoding

It was hypothesized that the individuals with a PED would differ from the NBDs at the phonological encoding stage. This hypothesis was supported, but the individuals with AoS also differed from the NBDs at the phonological encoding stage. The stimulus-locked difference between individuals with a PED and NBDs and the stimulus-locked difference between individuals with AoS and NBDs were observed in an earlier time window than the effect found on the word reading task Laganaro et al. (2013) used for the comparison of individuals with a phonological disorder and individuals with AoS to NBDs. The response-locked difference between individuals with AoS and NBDs largely overlapped with the effect found on the word reading task used by Laganaro et al. (2013). They did not find a difference in the timing in which individuals with a phonological disorder and individuals with AoS differed from NBDs. This difference in outcomes can be explained by the fact that Laganaro et al. (2013) used a reading task with words, whereas the current study used nonwords, which have a higher processing cost.

The stimulus-locked effect in the EEG data of the individuals with a PED showed a later attenuated positive peak compared to their matched NBDs. This attenuated peak suggests that there was a large difference in the waveform of the EEG among the individuals with a PED. Also, it could mean that the process of phonological encoding was much slower in the individuals with a PED. In the individuals with AoS, the positive peak was larger than the peak observed in their matched NBDs and there was no difference in the timing of the peak. This suggests that the process of phonological encoding was more comparable to the matched NBDs for individuals with AoS than it was for the individuals with a PED.

Phonetic encoding

It was hypothesized that only individuals with AoS should differ from the NBDs at the phonetic encoding stage. While the individuals with AoS did differ from the NBDs at the phonetic encoding stage, so did the individuals with a PED. The fact that individuals with a PED differed from NBDs at this stage implies that individuals with a PED were simultaneously encoding the second syllable of the nonword phonologically and the first syllable phonetically. Levelt et al. (1999) have suggested that phonetic encoding starts as soon as the first syllable is phonologically encoded, regardless of whether phonological encoding of the entire word has been completed. The disorder at the phonological encoding stage, thus, had an impact at the phonetic encoding stage, because there is interaction between the phonological and the phonetic encoding stage (Laganaro, 2005, 2008). The response-locked time window in which differences between the individuals with AoS and the NBDs were identified largely overlapped with the time window in which individuals with AoS differed from NBDs on the nonword reading task in the study by Laganaro (2011).

The EEG data of the individuals with AoS differed from the NBDs on nonwords with moderate syllable frequency, but not on nonwords with low syllable frequency. This suggests that individuals with AoS could not activate the articulation plans and therefore they needed to compute the articulation plans for nonwords with high, moderate and low syllable frequency on demand. This corresponds to the findings by Varley and Whiteside (2001), Varley et al. (2006) and Whiteside and Varley (1998). The syllable frequency effect we found on the accuracy suggests that individuals with AoS produced more errors when computing articulation plans for nonwords with low and moderate syllable frequency than for nonwords with high syllable frequency. This is in line with Varley et al. (2006) and Aichert and Ziegler (2004) who agree that syllable frequency effects can be observed in the higher frequency bounds. All syllables were above mean syllable frequency, so the NBDs could potentially have retrieved the articulation plans for all syllables. Retrieving articulation plans of lower frequency syllables requires more time than retrieving articulation plans of higher frequency syllables in NBDs (Levelt and Wheeldon, 1994). The increased processing time for retrieving articulation plans of low frequency syllables in the NBDs may have been somewhat comparable to the processing time for computing the articulation plans on demand in the individuals with AoS. Therefore, no difference between both participant groups was found on reading nonwords with low syllable frequency. The processing time required to retrieve the articulation plans for nonwords with moderate syllable frequency in the NBDs was less than the processing time required to compute the articulation plans on demand in the individuals with AoS. This explains why a difference between these participant groups was found on nonwords with moderate syllable frequency. The production of nonwords with high syllable frequency was not compared between the groups.

The stimulus-locked effect showed a negativity for individuals with a PED, which was not as strong in the NBDs. This suggests that the process that was taking place in the individuals with a PED was weaker in the NBDs at that point in time. The process that was observed in the NBDs was much weaker or not taking place in the individuals with AoS in that time window, as the response-locked effect showed a positivity in the waveform of the NBDs, which was not reflected in the waveform of the individuals with AoS.

4.4.3 Differences between individuals with a PED and individuals with AoS

As hypothesized, behavioural differences between individuals with a PED and individuals with AoS were found on the nonword reading task only. This was the most difficult task for the individuals with aphasia, because it targeted their impaired stages. Therefore they were not able to simultaneously respond quickly and accurately and a 'speed-accuracy tradeoff' (Brinley, 1965; Ratcliff et al., 2007) was observed. Individuals with AoS responded faster than individuals with a PED, but they made more errors. Both participant groups were required to respond quickly, as they had only 5 seconds to respond. An impairment at phonetic encoding was expected to reduce speed more than an impairment at phonological encoding, because phonetic encoding requires more time than phonological encoding in neurologically healthy adults (Indefrey, 2011). If the impaired phonetic encoding stage in individuals with AoS had a larger impact on speed, they should have responded more slowly than the individuals with a PED, which is not what we found. Thus, the individuals with AoS must have reduced their accuracy significantly. The higher accuracy in individuals with a PED can be explained by their opportunity to take more time to prepare the response, partially because their impairment had a smaller impact on speed.

It was hypothesized that individuals with AoS would differ from individuals with a PED at the phonetic encoding stage only. This hypothesis was supported by the findings of the current study. Only at the phonetic encoding stage, a difference was found when comparing the difference between individuals with a PED and their matched NBDs and the difference between individuals with AoS and their matched NBDs. The scalp distribution and the timing of this difference is shown in the last column of Figure 4.15. The waveform of the individuals with a PED compared to the NBDs and the waveform of the individuals with AoS compared to the NBDs had an identical morphology up to 300 ms after stimulus presentation. From this point onward, the waveform of the difference between individuals with a PED and NBDs showed an increasing negativity, which was absent in the waveform of the comparison between individuals with AoS and NBDs. A difference between the waveform of the difference between individuals with a PED and NBDs and the waveform of the difference between individuals with AoS and NBDs was observed starting 430 ms after stimulus presentation. This suggests that there was a difference in processing during phonetic encoding between the individuals with a PED and the individuals with AoS. This was supported by the fact that the individuals with AoS differed from the NBDs in a late response-locked time window only. In that response-locked time window, no difference was found between the individuals with a PED compared to the NBDs and the individuals with AoS compared to the NBDs. The effect was found in the time window during which individuals with a PED differed from the NBDs. This is in line with the EEG results on the comparisons between individuals with aphasia and their matched NBDs in this study. Individuals who have a disorder at a particular stage, seem to have attenuated waveforms as compared to the individuals without a disorder at that stage. For example, attenuated waveforms were found for the individuals with a PED at the phonological encoding stage and for the individuals with AoS at the phonetic encoding stage. Attenuated waveforms suggest that a process was weaker or not taking place at that point in time.

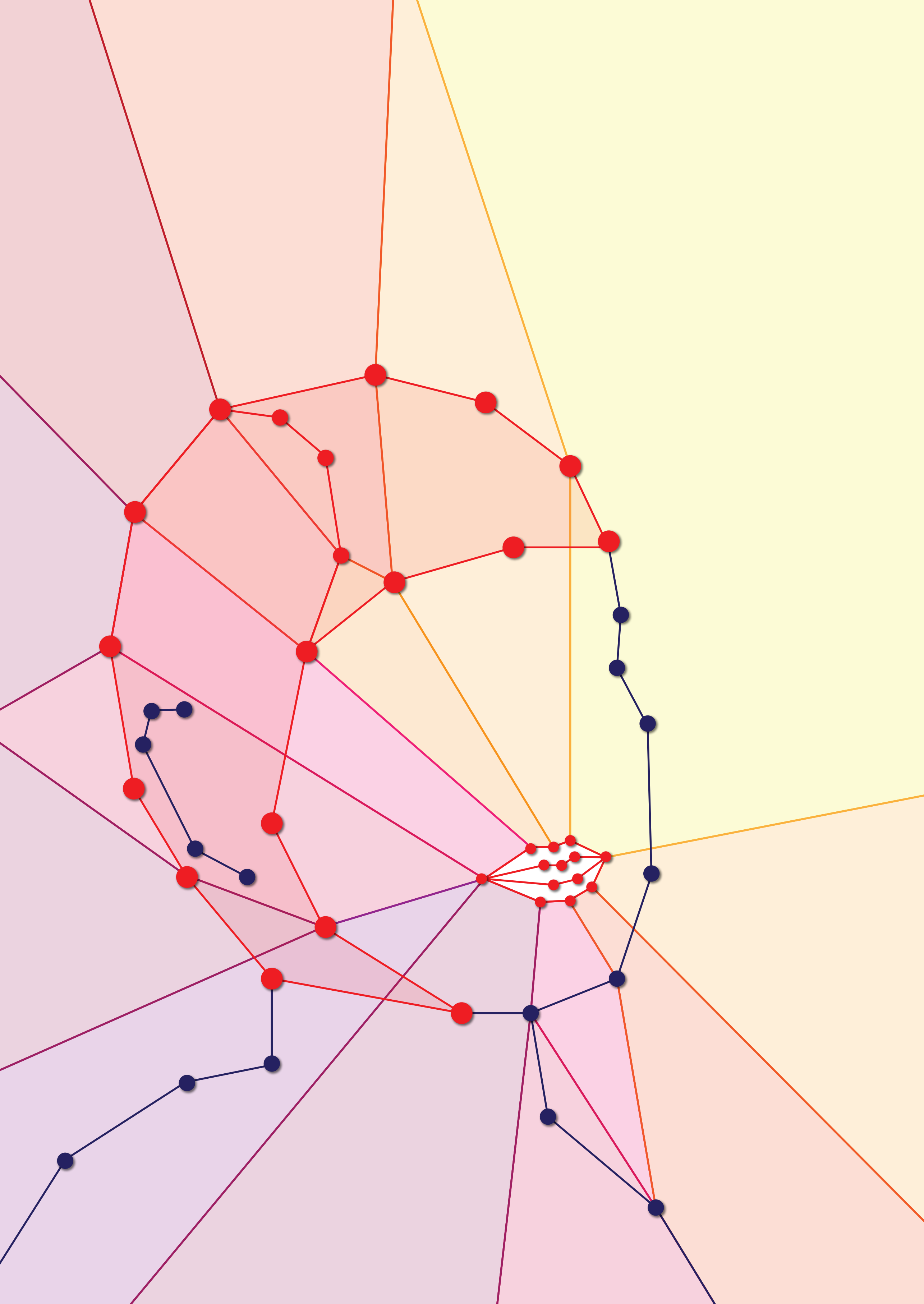
From these outcomes it can be concluded that the EEG protocol can be used to differentiate between individuals with a PED and individuals with AoS.

4.5 Conclusion

This is the first study to have tested all separate processing stages of the production of words and nonwords in the same two groups of aphasic speakers with speech production deficits. Their data were compared to those of two groups of age and gender matched NBDs. The aim of the project was to develop a protocol with EEG that can be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS. Nonword reading has proven to be a useful task for this purpose in three different analyses. For the identification of the speech production stages in both groups of individuals with aphasia, the EEG data of the individuals with a PED showed no effect of nonword length in phonemes, which was used to target phonological encoding. Also, the EEG data of the individuals with AoS showed no effect of syllable frequency of the nonwords, which was used to track phonetic encoding. This suggests that *not* showing an effect of a manipulation in the EEG data is a sign that a stage may be impaired. However, neither of the groups of individuals with aphasia showed a cumulative semantic interference effect at the lemma retrieval stage, so this needs to be applied with caution. For the comparison of the EEG data between individuals with aphasia and matched NBDs at the phonological and phonetic encoding stages, differences between individuals with a PED and NBDs were identified in earlier time windows than differences between individuals with AoS and NBDs. This corresponds to the model by Levelt et al. (1999) in which phonological encoding precedes phonetic encoding. It suggests that the timing of the difference between the individuals with aphasia and the NBDs in the EEG data can be used to identify the impaired stage, but this difference was not statistically significant. To differentiate both groups of individuals with aphasia, the EEG data of the difference between individuals with a PED and NBDs was compared to the difference between individuals with AoS and NBDs. This way, both groups of individuals with aphasia were differentiated at the phonetic encoding stage on reading nonwords with moderate syllable frequency by using EEG.

4.6 Clinical implications

Clinically, a PED and AoS are not always easy to distinguish in individuals with aphasia. However, since the underlying impairments are supposed to be different, they require different treatments. Two ways of classifying AoS do not seem to work out perfectly: some characteristics in speech production can be observed in both AoS and in a PED in aphasia and some brain lesion sites can be related to both AoS and aphasia. The current study shows that by using EEG it is possible to uncover the disordered process in a PED and in AoS in a group of individuals with aphasia. This is a first step towards a clinical protocol. If future investigations show that it is possible to distinguish the origin of the deficit at an individual level, this will provide the possibility of developing tailor-made treatment. In that case, the EEG procedure can be embedded in clinical practice. It is expected that EEG may not only be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS, but also in Childhood AoS, as in this field the same discussions apply.



Chapter 5

General discussion

5.1 Introduction

In the research presented in this thesis, speech production stages were identified using EEG in younger adults, older adults and individuals with aphasia. The goal was to see whether EEG can be used to differentiate aphasic individuals with a phonological encoding disorder (PED) from those suffering from Apraxia of Speech (AoS). The level of impairment causing speech sound errors differs between both groups of individuals with aphasia. In a PED, the errors arise due to a problem with the retrieval and/or the ordering of phonemes (Laganaro & Zimmermann, 2010; Laganaro, 2012). In AoS, the errors arise when movements for speech are programmed (Darley, Aronson, & Brown, 1975; Jonkers, Feiken, & Stuive, 2017; Miller & Wambaugh, 2017; Ziegler, 2008). In clinical practice, it is hard to identify the underlying level of impairment, because a pure PED (like conduction aphasia) is rare and pure AoS even more so, as AoS is usually accompanied with aphasia (Nicholas, 2005).

Two options to differentiate the disorders have been described in the literature, one based on characteristics in the speech and the other based on the brain lesion site. However, while there are some characteristics that are unique to AoS (Ballard et al., 2016; Jonkers et al., 2017), most of them can be observed in both PED and AoS. In addition, there is discussion about the specific characteristics of AoS (Jonkers et al., 2017). Also, unique brain lesion sites causing AoS have not been identified, with some sites, such as Broca's area, related to both AoS and aphasia (Bonilha, Moser, Rorden, Baylis, & Fridriksson, 2006; Hillis et al., 2004; Ogar et al., 2006; Richardson, Fillmore, Rorden, LaPointe, & Fridriksson, 2012; Square-Storer, Roy, & Martin, 1997; Trupe et al., 2013). As both characteristics and lesion site have been shown to be suboptimal to differentiate the underlying disorders, in the current study a new method was tested. In previous research, EEG was used to differentiate between a semantic impairment and a lexical disorder in individuals with aphasia (Laganaro et al., 2009). The goal of the current project was to study whether EEG could also be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS.

The process of speech production consists of several serial stages, as described in the model of spoken word production discussed in Chapter 1 (Indefrey & Levelt, 2004; Levelt, Roelofs, & Meyer, 1999). In previous studies, the time course of lemma retrieval (Costa, Strijkers, Martin, & Thierry, 2009), lexeme retrieval (Laganaro et al., 2009; Laganaro & Perret, 2011; Laganaro, Valente, & Perret, 2012; Valente, Bürki and Laganaro, 2014), phonological encoding (Laganaro, Python, & Toepel, 2013) and phonetic encoding (Bürki, Pellet-Cheneval, & Laganaro, 2015; Laganaro, 2011) have been identified using EEG, in different groups of neurologically healthy participants. The novelty of the current project was that all speech production stages were identified in one and the same group of participants. This meant that differences between participants did not vary between the experiments and could not influence the timing of the effects used to identify the stages. For example, whether participants were fast or slow speakers is known to have an impact on the timing of the AoA-effect (Laganaro et al., 2012). Because all stages within the process of speech production were studied within the current project, the coherence between the stages could be addressed. The observation of potential tradeoffs between stages provided new insights on the manifestation of the stages in individuals with aphasia. For the current project, a protocol with EEG was developed to track the speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding. EEG data were analyzed from stimulus onset until 100 ms before response onset. In this way, time windows after stimulus onset and time windows before response onset were investigated. In this chapter, research questions that were raised in experimental Chapters 2, 3 and 4 will be revisited and the findings will be discussed.

As a proof of principle study, the protocol was tested in neurologically healthy young adults. The tasks of the protocol and the findings of this study reported on in Chapter 2 will be discussed in Section 5.2. The protocol was developed for individuals with aphasia, who are usually older than the individuals included in the proof of principle study. Therefore, it was studied whether the protocol could also be used to track speech production stages in older adults. In addition, it was tested whether the speech production stages targeted in the protocol changed with age. The findings of this study were reported on in Chapter 3 and published in Den Hollander, Jonkers, Mariën and Bastiaanse (2019). The speech production stages in the neurologically healthy older adults will be discussed in Section 5.3, and the differences between the younger and older adults will be covered in Section 5.4. With the experiments reported on in Chapter 4, it was studied whether the protocol could be used to differentiate individuals with aphasia and a PED from individuals with aphasia and AoS. It was tested whether the protocol could be used to track the speech production stages in individuals with aphasia. Then, differences between individuals with aphasia and matched non-brain-damaged individuals, who are referred to as 'NBDs', were identified for every stage. Finally, differences between individuals with aphasia and a PED, who will be referred to as 'individuals with a PED', and matched NBDs were compared to differences between individuals with aphasia and AoS, who will be referred to as 'individuals with AoS', and matched NBDs were tested for every stage. The tracked stages in the individuals with aphasia will be discussed in Section 5.5, the comparison with the NBDs will be covered in Section 5.6 and the indirect comparison of both groups of individuals with aphasia will be reported on in Section 5.7. Section 5.8 provides directions for future research.

5.2 Tracking speech production stages in younger adults

Twenty young adults with an age range of 17 to 28 years were assessed with two picture naming tasks, a nonword reading task, and a nonword repetition task, while their brain activity was registered with EEG. In these tasks, items were manipulated for linguistic features that are known to influence the relevant stages.

Lemma retrieval

The first hypothesis was that lemma retrieval could be tracked using EEG when the items in the picture naming task were manipulated for the number of previously named pictures of a particular semantic category, inducing the 'cumulative semantic interference effect' (Costa, Strijkers, Martin, & Thierry, 2009; Howard, Nickels, Coltheart, & Cole-Virtue, 2006). During the lemma retrieval stage, semantically related neighboring lemma nodes are co-activated with the target lemma node. The target lemma node receives most activation and the target lemma can be retrieved. When lemmas that are semantically related to the target lemma have been previously retrieved, there is more competition between the lemma nodes. This leads to increased response times (Howard et al., 2006), which corresponded to the findings of the study reported in Chapter 2. Response times for naming the fifth picture of a particular semantic category were longer compared to response times for naming the first picture belonging to that same category. Differences in the EEG data between the first item and the fifth item of the same category were observed from 100 to 265 ms after stimulus onset and from 445 to 195 ms before response onset, indicating the time window of lemma retrieval. This time window largely overlaps with the time window in which the cumulative semantic interference effect was identified in the study by Costa et al. (2009). However, the time window related to the cumulative semantic interference effect identified in that study had a later onset, because words with a lower frequency were used.

Lexeme retrieval

Second, it was hypothesized that lexeme retrieval could be identified using EEG in a picture naming task in which the lexemes vary in age of acquisition (AoA). Naming speed was found to decrease as AoA increased, which has been reported in previous studies (Morrison & Ellis, 1995; Morrison, Ellis, & Quinlan, 1992). In the EEG data, the AoA-effect was observed from 100 to 300 ms after stimulus onset and from 475 to 330 ms before response onset, indicating the time window for lexeme retrieval. The time window of the stimulus-locked AoA-effect was comparable to the one identified by Laganaro and Perret (2011) using EEG. The response-locked time window of the AoA-effect was similar to the time windows found in EEG studies on the AoA-effect by Laganaro et al. (2012) and Valente et al. (2014).

Phonological encoding

The third hypothesis was that nonword length in number of phonemes could be used to track phonological encoding in a nonword reading task and a nonword repetition task by using EEG. As the number of phonemes in a nonword increases, more phonemes are phonologically encoded and have to be held in the phonological output buffer longer (Roelofs, 2004), which causes a larger processing load. In the reading task, the additional processing cost was observed as longer response times for nonwords that consisted of more phonemes. No such effect was found in the repetition task, which indicated that the repetition task was not optimal to track phonological encoding. Nonword length in phonemes may also have influenced grapheme-to-phoneme conversion, so it could be argued that it is a general processing cost. This would have caused an earlier onset of the nonword length in phonemes effect, because grapheme-to-phoneme conversion precedes phonological encoding. No previous EEG study has looked into grapheme-to-phoneme conversion, so its time window is unknown. In the EEG data recorded during the reading task, the effect of nonword length in phonemes was identified from 350 to 425 ms after stimulus presentation and from 335 to 320 ms before response onset. Given that only visual processing of the string of graphemes preceded grapheme-to-phoneme conversion, this onset of this effect seemed rather late to have impacted grapheme-to-phoneme conversion. The EEG results of the repetition task were not interpreted, because there was no effect of nonword length in phonemes in the behavioural data. In previous EEG studies, word length effects have been studied using picture naming tasks, but no effects of word length have been identified (Hendrix, Bolger, & Baayen, 2017; Valente et al., 2014). The phonological encoding of an unfamiliar string of phonemes in a nonword reading task possibly required more processing cost than the phonological encoding of a familiar lexeme in a picture naming task, which may explain why a length effect was found in the current study.

Phonetic encoding

Fourth, it was hypothesized that by using EEG, the phonetic encoding stage could be tracked in a nonword reading task and a nonword repetition task manipulated for syllable frequency. Phonetic encoding of low frequency syllables is more demanding than phonetic encoding of high frequency syllables. According to Levelt and Wheeldon (1994), articulatory plans for high frequency syllables can be retrieved from a syllabary, whereas plans for low frequency syllables need to be computed on demand. The effect of syllable frequency on phonetic encoding is widely acknowledged, but there is much debate about the existence of a syllabary (Laganaro & Alario, 2006; Laganaro, 2008). In the reading task, response times were found to increase as syllable frequency decreased. No such effect was observed in the repetition task, so this task was not usable to track phonetic encoding. In the EEG data recorded during the reading task, the syllable frequency effect was identified from 350 to 450 ms after stimulus onset and from 250 to 200 ms before response onset. The timing of the response-locked syllable frequency effect corresponded to the time window of this effect found in an EEG study by Laganaro (2011) in which a nonword reading task was used. The effect found in the current study was earlier than the syllable frequency effect identified in the EEG study by Bürki, Pellet-Cheneval and Laganaro (2015). The late effect found by Bürki et al. (2015) was related to complexity of the task used in that study, as phonemes were to be inserted into nonwords before they were read. The EEG data of the repetition task were not interpreted, as there was no effect of syllable frequency in the response time data.

Time course of the speech production stages

Based on previous MEG and EEG studies, Indefrey (2011) estimated the time windows of the speech production stages under study. The estimated time windows by Indefrey (2011) did not overlap, which is in line with the serial concept of the stages in the model by Levelt et al. (1999) and Indefrey and Levelt (2004). However, in our study on the time course of speech production in younger adults, overlap was found between the time windows of lemma retrieval and lexeme retrieval, but the time window of lemma retrieval ended earlier than the time window of lexeme retrieval. Such an overlap can be explained by interaction between the stages, as suggested, for example, by Dell (1986). In previous EEG studies, identical time windows have been reported for lemma and lexeme retrieval using lexical frequency effects (Levelt, Praamstra, Meyer, Helenius & Salmelin, 1998; Maess, Friederici, Damian, Meyer, & Levelt, 2002). However, frequency could not impact on the time window identified in the lemma retrieval task, because the items were controlled for lemma frequency. Moreover, semantic interference could not have impacted on the identified time window of the lexeme retrieval stage, because no more than two items of the same semantic category have been used in the lexeme retrieval task.

In the study with young adults, overlap was found in the time windows of phonological and phonetic encoding, but the time window of phonological encoding ended earlier than the time window for phonetic encoding in the reading task. This suggests that these processes interact (Dell, 1986). Levelt et al. (1999) also suggested that phonetic encoding starts as soon as a syllable is phonologically encoded, regardless of whether phonological encoding of the entire word has been completed. The repetition task was removed from the protocol, because it was unsuitable for tracking phonological and phonetic encoding. Hence, phonological end phonetic encoding were tracked using the reading task only in the experiments described in Chapters 3 and 4. A benefit of using the reading task was that visual input was processed, which made the reading task more comparable to the picture naming tasks than the repetition task, in which auditory input was processed. It was concluded that the picture naming tasks and the reading task in the protocol with EEG could be used to identify the speech production stages lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding.

5.3 Tracking speech production stages in older adults

The first aim of the second study reported on in Chapter 3 of this dissertation was to test whether the protocol with EEG could be used to track the four speech production stages in older adults. In the twenty older adults with an age range from 40 to 65 years (comparable to the group of aphasic speakers), effects of cumulative semantic interference, AoA, nonword length in phonemes and syllable frequency were reflected in the response times of the picture naming tasks and the nonword reading task. In the EEG data, the cumulative semantic interference effect tracking lemma retrieval was found from 540 to 450 ms before response onset. The AoA-effect targeting lexeme retrieval was observed in the EEG data from 430 to 140 ms before response onset. This effect overlapped with the AoA-effects identified by Laganaro et al. (2012) and Valente et al. (2014). From 100 to 135 ms and from 280 to 300 ms after stimulus presentation, the effect of nonword length in phonemes identifying phonological encoding was tracked in the EEG data. The syllable frequency effect targeting phonetic encoding was found in the EEG data from 280 to 455 ms after stimulus presentation as well as from 455 to 435 ms before response onset. The response-locked effect was earlier than the syllable frequency effect identified by Laganaro (2011). The nonwords used by Laganaro (2011) possibly had a more complex syllable structure than the nonwords used in the current study. Corresponding to Indefrey's (2011) estimations for the sequential nature of the speech production stages, lemma retrieval preceded lexeme retrieval. Despite a small overlap in the time windows, phonological encoding was observed in an earlier time window than phonetic encoding. This implied that phonetic encoding started before phonological encoding was completed, as suggested by Levelt et al. (1999). Thus, the protocol with EEG could be used to identify the speech production stages in older adults.

5.4 Speech production stages in younger versus older adults

The second aim of this study described in Chapter 3 was to test whether the speech production stages changed with age. The time windows of the effects in the younger adults, the older adults and the difference between the two participant groups per task are shown in Figure 5.1.

The duration of lemma retrieval was hypothesized to increase in older as compared to younger adults, because semantic memory (Cardenas et al., 2011; Harada, Natelson Love, & Triebel, 2013) and inhibition (Harada et al., 2013) decline with aging. During lemma retrieval, activating semantically related lemma nodes relies on semantic memory. Inhibition of neighboring lemma nodes is required to select the target lemma. The longer duration for lemma retrieval was expected to delay the onset of the lexeme retrieval stage in the older adults. As hypothesized, the lexeme retrieval stage started later for the older adults than for the younger adults. The duration of the lemma retrieval stage and the duration of the lexeme retrieval stage were not increased for older as compared to younger adults. Yet, slower response times were observed for older adults than for younger adults on both picture naming tasks. The observation of shorter instead of longer time windows in older adults may have a neurophysiological explanation. In older adults, neurons that fire together are possibly less synchronous in their timing, less aligned regarding their geometry or the effect has a more variable latency (Wlotko, Lee, & Federmeier, 2010). The current from the dipoles can only be measured at the scalp when large clusters of pyramidal neurons, which are positioned in parallel, simultaneously show the same type of postsynaptic potential (Pascual-Marqui, Sekihara, Brandeis, & Michel, 2009). Therefore, the time window in which all participants showed an effect was shorter.

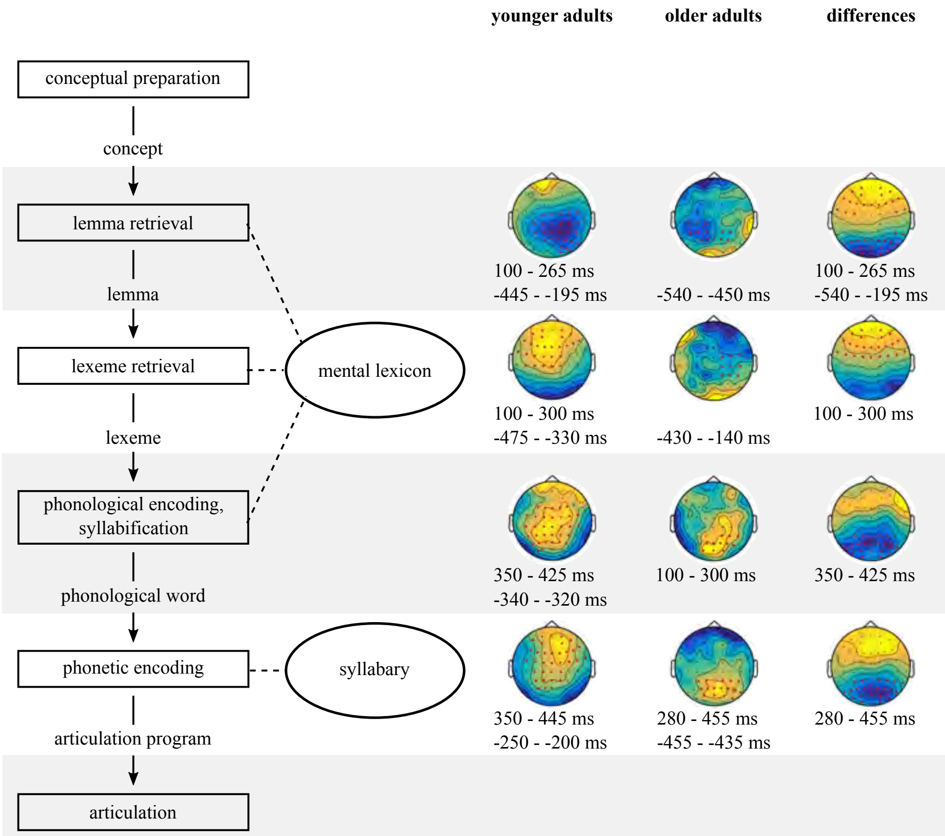


Figure 5.1: Time windows of the cumulative semantic interference effect (first row), the AoA effect (second row), the nonword length in phonemes effect (third row) and the syllable frequency effect (fourth row) in the EEG data of the younger (first column) and the older adults (second column). Differences between younger and older adults per stage (third column).

Lemma and lexeme retrieval were expected to change with age, but in the nonword reading paradigm these stages are not addressed. Thus, phonological and phonetic encoding were hypothesized not to be delayed in the older adults (Tremblay & Deschamps, 2016). Earlier onsets were observed for the older adults than for the younger adults. This may be explained by the fact that, at the stages preceding phonological encoding, visual analysis and grapheme-to-phoneme conversion took place. The efficiency of the visual network is maintained with aging (Geerligs et al., 2015) and, therefore, visual analysis is not expected to have been different in the older adults as compared to the younger adults. Possibly, the older adults were quicker at grapheme-to-phoneme conversion than the younger adults, because the older adults have more years of experience with reading. However, no previous studies have looked into aging effects on grapheme-to-phoneme conversion, but a decline in reading speed has been observed in older adults compared to younger adults (Chen, Khalid & Buari, 2019; Den Hollander et al., 2019).

Even though the older adults responded more slowly than the younger adults on every task, this was not always reflected in the timing of the speech production stages in the EEG data. The older adults may have responded more slowly than the younger adults, because they may have checked whether the response was correct after planning the articulation. It has been hypothesized that, in contrast to the younger adults, older adults cannot focus on speed and accuracy at the same time (Ratcliff, Thapar, & McKoon, 2007). It may be that the older adults focused on accuracy and collected more information before responding (Rabbitt, 1979). In that case, the timing of the speech production stages in the older adults could be different, but did not have to be delayed compared to the younger adults.

To test whether the time windows of the speech production stages differed between the older and the younger adults, both groups were compared in time windows in which at least one of the groups showed an effect related to a speech production stage. Differences between older and younger adults were mostly found in stimulus-locked time windows. The visual network, which is used for visual processing of the stimulus immediately upon its presentation, was not expected to change with age (Geerligs et al., 2015). After visual processing is completed, higher cognitive function networks are involved in the speech production stages. With aging, a decrease in local efficiency of these networks may alter the neural signature or the timing of the stages, which was reflected in the EEG data.

Finally, it was hypothesized that the scalp distributions of speech production stages did not change with age, because the same group of neurons was expected to be involved in the stages in neurologically healthy individuals. This hypothesis was supported. It was concluded that the speech production stages changed with age regarding their timing, but they did not change regarding their neural configuration.

5.5 Tracking speech production stages in individuals with aphasia

In previous EEG studies on speech production in individuals with aphasia and/or AoS (Laganaro, 2011; Laganaro et al., 2009, 2013), comparisons between NBDs and patients were only based on the stages identified in the NBDs, whereas in this dissertation all stages were identified in both the NBDs (Chapter 3; Den Hollander et al., 2019) and in the individuals with aphasia in the study presented in Chapter 4. The research question in Chapter 4 was whether these stages could be demonstrated by using EEG in individuals with aphasia and a PED and in individuals with aphasia and AoS. It was hypothesized that the effects used to track the speech production stages would be reflected in the accuracy data, the response time data and the EEG data of the individuals with aphasia. Sixteen individuals with aphasia, including eleven with AoS, were tested with the protocol to identify the speech production stages. Figure 5.2 gives an overview of the timing of the identified speech production stages in the EEG data of the NBDs, the individuals with a PED and the individuals with AoS.

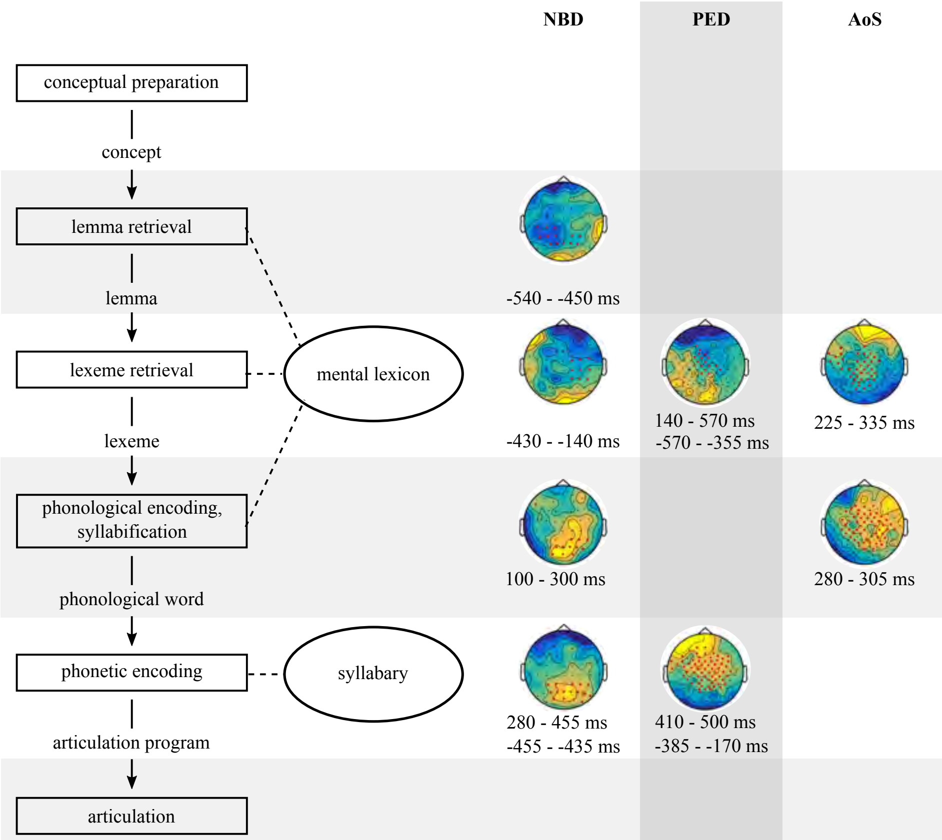


Figure 5.2: Timing and scalp distribution of the speech production stages that could be identified in the EEG data of the NBDs (the older adults from Chapter 3 shown in the first column), the individuals with a PED (second column) and the individuals with AoS (third column) using the cumulative semantic interference effect (first row) and the AoA effect (second row) in picture naming and the nonword length in phonemes effect (third row) and the syllable frequency effect (fourth row) in nonword reading. No timing and scalp distribution is shown for stages that could not be identified. Time windows with positive values are stimulus-locked and those with negative values are response-locked.

Lemma and lexeme retrieval

The cumulative semantic interference effect was reflected in the response time data of the individuals with AoS, but not in the behavioural data of the individuals with a PED. The lemma retrieval stage could not be tracked, because the cumulative semantic interference effect was not observed in the EEG data. Possibly the EEG response to the cumulative semantic interference effect varied between participants with AoS, so no cluster was identified. The AoA effect was reflected in the accuracy of the individuals with AoS, but not in the individuals with a PED. In both groups of individuals with aphasia, the lexeme retrieval stage was identified using the AoA effect. The discrepancy between online and offline outcomes observed in the individuals with a PED was found in previous research on individuals with aphasia (Dickey, Choy, & Thompson, 2007). The AoA effect was observed from 140 to 155 ms and from 475 to 570 ms after stimulus presentation in the EEG data of the individuals with a PED. Also, a response-locked AoA effect was found from 570 to 355 ms before response onset. The duration between the response-locked AoA effect and the response was increased in the individuals with a PED compared to the older NBDs described in Chapter 3. Lexeme retrieval preceded phonological encoding, for which individuals with a PED required more time. In the individuals with AoS, the AoA effect was observed from 225 to 335 ms after stimulus presentation.

Phonological and phonetic encoding

The effect of nonword length in phonemes and the syllable frequency effect were observed in the accuracy data of the individuals with AoS, but not in the individuals with a PED. The EEG data of the individuals with a PED did not reveal any effect of nonword length in phonemes, which was used to target phonological encoding. In the EEG data of the individuals with AoS, a nonword length in phonemes effect was observed from 280 to 305 ms after stimulus presentation. The effect had a later onset in the individuals with AoS than in the older NBDs described in Chapter 3, which suggests that the phonological encoding stage was delayed in the individuals with AoS. Some interference from the phonetic encoding stage may have reduced the duration of the effect.

The syllable frequency effect was observed in the EEG data of individuals with a PED from 410 to 500 ms after stimulus presentation and from 385 to 170 ms before response onset. Compared to the older NBDs described in Chapter 3, these effects took place later, because the individuals with a PED required more time for the preceding phonological encoding stage. The individuals with AoS did not show an effect of syllable frequency in the EEG data. So, a discrepancy between online and offline measures was found in both groups of individuals with aphasia (Dickey et al., 2007). The severity of the AoS varied between participants, which may have modulated the individual EEG response to the syllable frequency effect, so no cluster could be identified. In addition, the absence of a syllable frequency effect in the EEG data implies that individuals with AoS could not activate articulation plans, so they had to compute all articulatory plans on demand (Varley & Whiteside, 2001; Varley, Whiteside, Windsor, & Fisher, 2006; Whiteside & Varley, 1998). Consequently, their production of high, moderate and low frequency syllables was impaired, but they produced more errors when computing articulation plans for nonwords with moderate and low syllable frequency than for nonwords with high syllable frequency. When comparing the EEG data of individuals with AoS to the NBDs, we found a difference on nonwords with moderate syllable frequency only. The difference between individuals with a PED and NBDs on nonwords with moderate syllable frequency had a longer duration than the difference between these groups on nonwords with low syllable frequency. This is in line with Varley et al. (2006) and Aichert and Ziegler (2004), who suggest that the syllable frequency effect can be observed in the higher frequency bounds.

5.6 Speech production stages in individuals with aphasia versus NBDs

The research question was at which stages individuals with a PED and individuals with AoS differed from NBDs who were matched for age and gender to the individuals with aphasia. They were selected from the group of older adults who participated in the study described in Chapter 3. The level of impairment in the individuals with aphasia had an impact on the picture naming tasks and the nonword reading task: they had lower accuracy and slower response times than the NBDs on all tasks. Differences between the individuals with aphasia and the NBDs were hypothesized to be observable in the EEG data at the stages that were impaired in the individuals with aphasia (e.g. Laganaro, 2011; Laganaro et al. 2009, 2013). Figure 5.3 shows the timing of the differences between individuals with aphasia and matched NBDs per speech production stage observed in the EEG data.

Lemma and lexeme retrieval

The majority of the individuals with aphasia had word finding difficulties caused by an impairment of lemma and/or lexeme retrieval. Differentiating these two impairments is complicated (e.g. Howard & Gatehouse, 2006). Hence, it was hypothesized that individuals with aphasia differed from the NBDs at the lemma and/or lexeme retrieval stage. At the lemma retrieval stage, individuals with a PED differed from the NBDs from 130 to 175 ms and from 290 to 445 ms after stimulus presentation. These time windows were similar to those in which Laganaro et al. (2009) found differences between individuals with aphasia and NBDs. The differences from 600 to 500 and from 190 to 165 ms before response onset found in the study described in Chapter 4 could not be compared to a previous study, as no response-locked effects were reported by Laganaro et al. (2009).

Both groups of individuals with aphasia differed from NBDs at the lexeme retrieval stage in the study described in Chapter 4. Differences between both groups of individuals with aphasia and NBDs were observed from 295 to 520 ms after stimulus presentation in the comparison with individuals with a PED and from 360 to 525 ms after stimulus presentation in the comparison with individuals with AoS. Laganaro et al (2013) also found that individuals with a phonological disorder and individuals with AoS differed from NBDs in comparable time windows on a picture naming task. The time window reported by Laganaro et al. (2013) was similar to the time window in which individuals with AoS differed from NBDs in the study described in Chapter 4. The stimulus-locked effect of the individuals with a PED started earlier than that found by Laganaro et al. (2013). This was also the case for the response-locked differences found in the individuals with a PED from 600 to 290 ms before response onset. This can be explained by the fact that the items we used in the protocol were shorter and had a higher frequency than those of Laganaro et al. (2013).

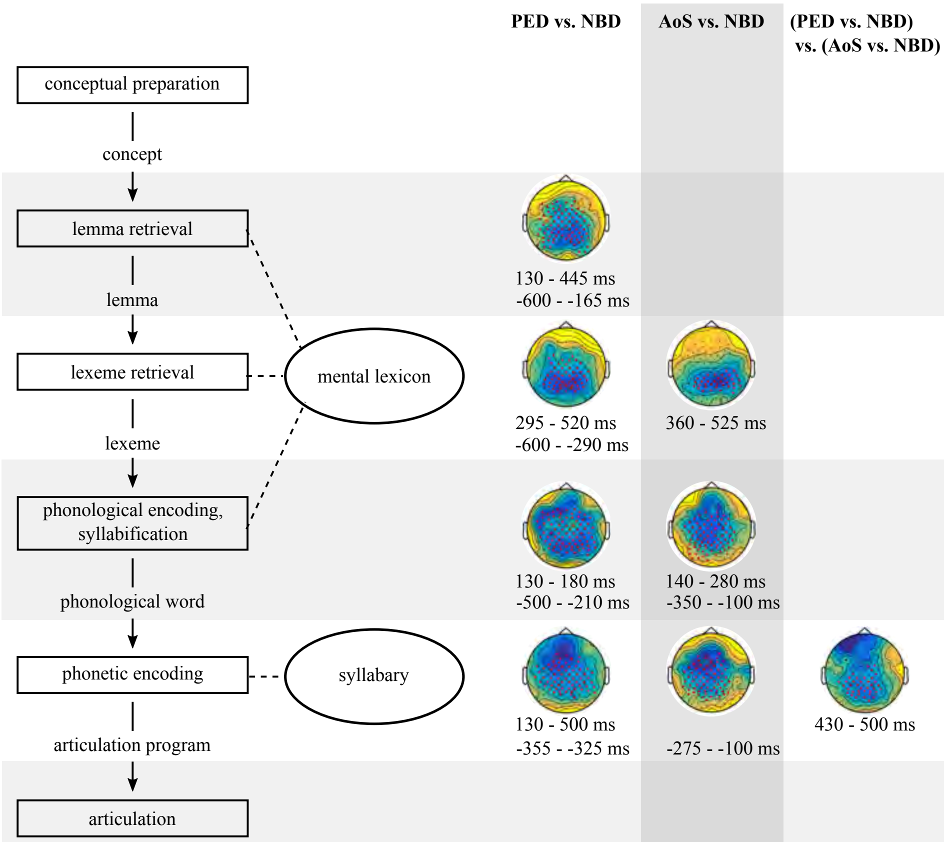


Figure 5.3: Timing and scalp distribution of the differences in the EEG data between individuals with a PED (first column) and matched NBDs and between individuals with AoS and matched NBDs (second column) and the difference between these differences (third column) identified per speech production stage. Time windows with positive values are stimulus-locked and those with negative values are response-locked.

5

Phonological and phonetic encoding

As hypothesized, the individuals with a PED differed from the NBDs at the phonological encoding stage. Differences between individuals with a PED and NBDs were found from 130 to 180 ms after stimulus presentation. The differences between individuals with AoS and NBDs were identified from 140 to 280 ms after stimulus presentation. Variation in the severity of the PED between participants may have impacted on the duration of the cluster in the individuals with a PED. Also, individuals with a PED differed from NBDs from 500 to 210 ms before response onset. The individuals with AoS also differed from the NBDs at the phonological encoding stage. The response-locked difference between individuals with AoS and NBDs was from 350 to 100 ms before response onset. In a reading task with words, Laganaro et al. (2013) found that both individuals with a phonological disorder and individuals with AoS differed from NBDs in a time window that largely overlapped with the response-locked time window in which differences between individuals with AoS and NBDs were found in the study described in Chapter 4.

Only individuals with AoS were expected to differ from NBDs at the phonetic encoding stage. Individuals with AoS differed from NBDs on reading nonwords with moderate syllable frequency from 275 to 100 ms before response onset, which was similar to the time window in which Laganaro (2011) found a difference between individuals with AoS and NBDs. This suggests, that individuals with AoS had to compute articulatory plans for syllables with low frequency on demand, and the retrieval of articulation plans for low frequency syllables by the NBDs had a comparable processing time, so no difference was found for items with low syllable frequency. Also, the findings imply that the NBDs required less processing time when retrieving the articulatory plans for syllables with moderate frequency, while the individuals with AoS had to compute them on demand, because they could not activate the articulation plans. This is in line with the findings by Varley and Whiteside (2001), Varley et al. (2006) and Whiteside and Varley (1998). Both Varley et al. (2006) and Aichert and Ziegler (2004) agree that syllable frequency effects can be observed in the higher frequency bounds. This was supported by our syllable frequency effect on the accuracy: individuals with AoS produced more errors when computing articulation plans for nonwords with low and moderate syllable frequency than for nonwords with high syllable frequency.

In contrast to expectations, the individuals with a PED also differed from the NBDs at the phonetic encoding stage. This can be explained by an interaction between the phonological and phonetic encoding stages (Laganaro, 2005, 2008). Levelt et al. (1999) suggested that phonetic encoding of the first syllable starts as soon as the first syllable has been phonologically encoded. Therefore, the impact of the individuals' phonological encoding disorder was also observed during phonetic encoding. Differences between individuals with a PED and NBDs were found from 130 to 190 ms after response onset for items with low syllable frequency. For items with moderate syllable frequency these groups differed from 390 to 500 ms after stimulus presentation and from 355 to 325 ms before response onset.

5.7 Speech production stages in individuals with a PED versus individuals with AoS

In line with our hypothesis, behavioural differences between the groups of individuals with aphasia were observed on the nonword reading task that targeted their impaired stage. They could not simultaneously respond quickly and accurately, which is known as the 'speed-accuracy tradeoff' (Brinley, 1965; Ratcliff et al., 2007). Individuals with AoS responded faster than individuals with a PED, but they made more errors. Individuals with a PED probably had more time to prepare their response, because phonological encoding is faster than phonetic encoding in neurologically healthy adults (Indefrey, 2011). Therefore, the accuracy of the individuals with a PED was higher. In turn, individuals with AoS probably reduced their accuracy significantly.

The difference in the EEG data between individuals with a PED and NBDs differed from the difference in the EEG data between individuals with AoS and NBDs only at the phonetic encoding stage, on nonwords with moderate syllable frequency. The timing of this difference was from 430 to 500 ms after stimulus onset, as shown in Figure 5.3. In this time window, the waveform of the difference between individuals with a PED and NBDs was negative going, whereas the difference between individuals with AoS and NBDs did not show this negativity. This indicates that there was a difference in processing at the phonetic encoding stage between the individuals with a PED and the individuals with AoS. This is supported by the fact that individuals with AoS differed from the NBDs only in a response-locked time window.

It was concluded that the protocol with EEG can be used to differentiate between individuals with aphasia and a PED and individuals with aphasia and AoS. Both groups were distinguished using a reading task for nonwords that were manipulated for syllable frequency. To differentiate the groups, the EEG data of the difference between individuals with a PED and matched NBDs was compared to the difference between individuals with AoS and matched NBDs. This is the first step for developing a protocol that can be used in clinical practice to track the source of the impairment underlying the production of speech sound errors using EEG in individuals with aphasia.

5.8 Directions for future research

The current project resulted in a protocol that can be used to distinguish a group of individuals with aphasia and a PED from a group of individuals with aphasia and AoS. In this section, suggestions for future applications of the protocol are provided. In addition to the outcomes of the current study, it could be investigated whether the protocol with EEG can also be used in Childhood AoS, as in this field the same discussions apply. However, first the protocol should be tested with typically developing children, as the timing of their speech production stages may be different from neurologically healthy adults.

Another way to proceed this line of research is the development of the EEG-protocol for clinical practice for individual application. If it is possible to identify the affected stage using the protocol, an individual with aphasia could then be treated with individually tailored therapy. Also, it could be studied whether therapy induced improvements in the disordered speech production stage can be assessed using the protocol with EEG.

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Appendix 1

to Chapters 2, 3 and 4

List of items used in the lemma retrieval task.

Item	Noun	Translation	Category	Translation	Lemma frequency	List 1: No. in category	List 2: No. in category	List 1: lag	List 2: lag
1	korst	crust	afval	trash	1.1139	1	5	0	5
2	as	ash	afval	trash	1.0792	3	3	7	6
3	schil	peel	afval	trash	0.7782	5	1	3	0
4	pit	pit	afval	trash	0.4771	2	4	5	7
5	graat	bone	afval	trash	0.301	4	2	6	3
6	schilder	painter	beroepen	professions	1.4472	1	5	0	3
7	tandarts	dentist	beroepen	professions	1.0792	4	2	6	4
8	bakker	baker	beroepen	professions	1.1139	2	4	3	5
9	kapper	barber	beroepen	professions	1	3	3	5	6
10	slager	butcher	beroepen	professions	0.9542	5	1	4	0
11	boek	book	bureauwaren	office ware	2.5877	2	4	6	3
12	brief	letter	bureauwaren	office ware	2.301	3	3	3	5
13	pen	pen	bureauwaren	office ware	1.2788	5	1	4	0
14	schrift	notebook	bureauwaren	office ware	1	1	5	0	6
15	schaar	scissors	bureauwaren	office ware	0.8451	4	2	5	4
16	hond	dog	dieren	animals	2.2253	4	2	6	4
17	paard	horse	dieren	animals	2.1987	1	5	0	3
18	koe	cow	dieren	animals	1.5563	2	4	3	5
19	schaap	sheep	dieren	animals	1.415	3	3	5	6
20	muis	mouse	dieren	animals	1.3222	5	1	4	0
21	brood	bread	eten	food	1.8451	1	5	0	6
22	ei	egg	eten	food	1.8261	4	2	5	2
23	kaas	cheese	eten	food	1.7243	3	3	3	5
24	worst	sausage	eten	food	1.0414	5	1	2	0

Item	Noun	Translation	Category	Translation	Lemma frequency	List 1: No. in category	List 2: No. in category	List 1: lag	List 2: lag
25	taart	cake	eten	food	1	2	4	6	3
26	staart	tail	haardrachten	hairstyles	1.5051	2	4	4	6
27	baard	beard	haardrachten	hairstyles	1.3617	3	3	6	6
28	snor	moustache	haardrachten	hairstyles	1.2304	1	5	0	4
29	vlecht	braid	haardrachten	hairstyles	0.9031	4	2	6	7
30	kuif	crest	haardrachten	hairstyles	0.4771	5	1	7	0
31	deur	door	huisonderdelen	house parts	2.5752	1	5	0	7
32	raam	window	huisonderdelen	house parts	2.2405	2	4	7	6
33	trap	stairs	huisonderdelen	house parts	2.0645	4	2	3	3
34	vloer	floor	huisonderdelen	house parts	1.8261	5	1	3	0
35	dak	roof	huisonderdelen	house parts	1.7559	3	3	6	3
36	weg	road	infrastructuur	infrastructure	2.6325	1	5	0	3
37	stad	city	infrastructuur	infrastructure	2.5092	2	4	3	3
38	dorp	village	infrastructuur	infrastructure	2.1367	4	2	6	7
39	brug	bridge	infrastructuur	infrastructure	1.716	3	3	3	6
40	stoep	sidewalk	infrastructuur	infrastructure	1.2304	5	1	7	0
41	vlieg	fly	insecten	insects	1.2553	3	3	6	7
42	worm	worm	insecten	insects	1	5	1	6	0
43	spin	spider	insecten	insects	0.9542	1	5	0	5
44	mier	ant	insecten	insects	0.8451	2	4	5	6
45	rups	caterpillar	insecten	insects	0.4771	4	2	7	6
46	glas	glass	keukengerei	kitchen ware	2.1847	1	5	0	4
47	mes	knife	keukengerei	kitchen ware	1.6128	2	4	4	6
48	pan	pan	keukengerei	kitchen ware	1.5441	3	3	6	2
49	vork	fork	keukengerei	kitchen ware	1.0792	5	1	4	0
50	zeef	sieve	keukengerei	kitchen ware	0.6021	4	2	2	4
51	broek	pants	kleding	clothes	1.7853	4	2	6	4
52	jas	coat	kleding	clothes	1.6902	5	1	4	0

Item	Noun	Translation	Category	Translation	Lemma frequency	List 1: No. in category	List 2: No. in category	List 1: lag	List 2: lag
53	jurk	dress	kleding	clothes	1.6232	3	3	2	6
54	rok	skirt	kleding	clothes	1.4914	1	5	0	4
55	trui	sweater	kleding	clothes	1.301	2	4	4	2
56	oog	eye	lichaamsdelen	body parts	2.9138	2	4	6	3
57	kin	chin	lichaamsdelen	body parts	1.515	5	1	2	0
58	oor	ear	lichaamsdelen	body parts	2.0414	4	2	5	2
59	neus	nose	lichaamsdelen	body parts	2.0043	1	5	0	6
60	tong	tongue	lichaamsdelen	body parts	1.7324	3	3	3	5
61	hut	hut	locaties	locations	1.5911	5	1	7	0
62	tent	tent	locaties	locations	1.4314	1	5	0	6
63	kooi	cage	locaties	locations	1.3617	2	4	6	2
64	stal	stable	locaties	locations	1.301	4	2	5	7
65	huis	house	locaties	locations	2.7993	3	3	2	5
66	bed	bed	meubilair	furniture	2.4771	1	5	0	4
67	stoel	chair	meubilair	furniture	2.179	5	1	6	0
68	bank	couch	meubilair	furniture	2.0569	2	4	4	5
69	kast	wardrobe	meubilair	furniture	1.6812	4	2	3	6
70	wieg	cradle	meubilair	furniture	1.0414	3	3	5	3
71	zak	sack	opbergers	storage	2.0531	5	1	3	0
72	kist	chest	opbergers	storage	1.6532	3	3	6	5
73	doos	box	opbergers	storage	1.5911	2	4	4	6
74	tas	bag	opbergers	storage	1.5798	1	5	0	4
75	mand	basket	opbergers	storage	1.301	4	2	5	3
76	foehn	hairdryer	persoonlijke verzorging	personal care	0	1	5	0	4
77	douche	shower	persoonlijke verzorging	personal care	1.2304	4	2	3	6
78	zeep	soap	persoonlijke verzorging	personal care	1.2041	3	3	5	3
79	kam	comb	persoonlijke verzorging	personal care	0.9031	2	4	4	5
80	vijl	file	persoonlijke verzorging	personal care	0	5	1	6	0

Item	Noun	Translation	Category	Translation	Lemma frequency	List 1: No. in category	List 2: No. in category	List 1: lag	List 2: lag
81	boom	tree	planten	plants	2.1367	3	3	6	6
82	struik	bush	planten	plants	1.4771	5	1	7	0
83	roos	rose	planten	plants	1.4624	2	4	6	6
84	heg	hedge	planten	plants	0.7782	4	2	6	7
85	tulp	tulip	planten	plants	0.4771	1	5	0	6
86	vlieger	kite	speelgoed	toys	0.7782	4	2	6	6
87	puzzel	puzzle	speelgoed	toys	0.6021	1	5	0	2
88	schommel	swing	speelgoed	toys	0.301	3	3	7	6
89	zandbak	sandbox	speelgoed	toys	0.301	2	4	2	7
90	glijbaan	slide	speelgoed	toys	0	5	1	6	0
91	boog	bow	sportvoorwerpen	sport ware	1.6628	2	4	4	6
92	schaats	skate	sportvoorwerpen	sport ware	0.4771	3	3	6	2
93	slee	sleigh	sportvoorwerpen	sport ware	0.301	1	5	0	4
94	pijl	arrow	sportvoorwerpen	sport ware	1.2041	4	2	2	4
95	ski	ski	sportvoorwerpen	sport ware	0	5	1	4	0
96	reus	giant	sprookjesfiguren	fairy-tale characters	1.2553	3	3	7	6
97	heks	witch	sprookjesfiguren	fairy-tale characters	1.2553	1	5	0	2
98	spook	ghost	sprookjesfiguren	fairy-tale characters	1.1139	5	1	6	0
99	draak	dragon	sprookjesfiguren	fairy-tale characters	0.9542	2	4	2	7
100	fee	fairy	sprookjesfiguren	fairy-tale characters	0.4771	4	2	6	6
101	vliegtuig	airplane	transport	transport	1.716	1	5	0	2
102	motor	motorcycle	transport	transport	1.6902	5	1	6	0
103	taxi	taxi	transport	transport	1.4624	2	4	2	5
104	tractor	tractor	transport	transport	0.6021	3	3	5	3
105	scooter	scooter	transport	transport	0	4	2	3	6
106	schep	shovel	tuingereedschap	garden tools	1.8976	2	4	3	3
107	bijl	axe	tuingereedschap	garden tools	1.0414	4	2	6	7
108	zaag	saw	tuingereedschap	garden tools	0.4771	5	1	7	0

Item	Noun	Translation	Category	Translation	Lemma frequency	List 1: No. in category	List 2: No. in category	List 1: lag	List 2: lag
109	kwast	brush	tuingereedschap	garden tools	0.699	1	5	0	3
110	hark	rake	tuingereedschap	garden tools	0.301	3	3	3	6
111	fles	bottle	vloeistofdispensers	liquid dispensers	2.0492	3	3	6	7
112	kraan	tap	vloeistofdispensers	liquid dispensers	1.1461	1	5	0	6
113	put	put	vloeistofdispensers	liquid dispensers	1	4	2	7	6
114	kan	pitcher	vloeistofdispensers	liquid dispensers	0.301	2	4	6	6
115	tap	faucet	vloeistofdispensers	liquid dispensers	0.4771	5	1	6	0
116	kip	chicken	vogels	birds	1.5185	2	4	6	6
117	eend	duck	vogels	birds	1.3802	4	2	7	2
118	haan	rooster	vogels	birds	1.2304	3	3	6	7
119	gans	goose	vogels	birds	1.0792	5	1	2	0
120	zwaan	swan	vogels	birds	0.9031	1	5	0	6
121	citroen	lemon	vruchten	fruits	1.0414	4	2	7	6
122	tomaat	tomato	vruchten	fruits	0.9542	3	3	7	7
123	banaan	banana	vruchten	fruits	0.7782	2	4	3	7
124	meloen	melon	vruchten	fruits	0.4771	5	1	6	0
125	pompoen	pumpkin	vruchten	fruits	0.301	1	5	0	3

Appendix 2

to Chapters 2, 3 and 4

List of items used in the lexeme retrieval task.

Item	Noun	Translation	Age of Acquisition	Lexeme frequency
1	anker	anchor	7.73	0.9031
2	armband	bracelet	5.75	0.4771
3	baard	beard	5.48	1.2788
4	balkon	balcony	7.78	1.1461
5	ballon	balloon	4.48	0.6021
6	bel	bell	5.28	1.2788
7	beschuit	rusk	6.65	0
8	blik	container	9.41	2.2148
9	boek	book	4.55	2.3979
10	boog	bow	6.45	1.6232
11	borstel	brush	5.38	0.4771
12	brief	letter	5.74	2.0569
13	bril	glasses	5.38	1.5051
14	broek	pants	4.19	1.7482
15	brood	bread	4.01	1.7924
16	brug	bridge	5.47	1.6128
17	bruid	bride	7.56	1
18	bus	bus	4.99	1.5441
19	circus	circus	6.15	0.7782
20	citroen	lemon	5.36	0.9542
21	clown	clown	5.05	0.6021
22	deeg	dough	6.74	0.8451
23	deken	blanket	5.19	1.1461
24	deksel	lid	6.45	1.1761
25	douche	shower	6.03	1.2041
26	drop	liqourice	7.84	0.301
27	eikel	acorn	7.31	0.4771
28	engel	angel	5.98	1.1761
29	ezel	donkey	5.61	0.9031
30	fabriek	factory	7.28	1.4624
31	fiets	bike	4.42	1.6232
32	fles	bottle	4.91	1.8692
33	fluit	flute	6.04	0.699
34	gans	goose	5.73	0.6021
35	geld	money	5.34	2.4409
36	geweer	gun	6.34	1.5051
37	gieter	watering can	6.18	0
38	gordijn	curtain	6.11	1.1761
39	graat	bone	7.11	0
40	haai	shark	6.32	0

Item	Noun	Translation	Age of Acquisition	Lexeme frequency
41	hak	heel	7.78	0.7782
42	hamer	hammer	6.5	0.9031
43	haring	herring	8.54	0.6021
44	hark	rake	7.46	0
45	hek	fence	6.15	1.3979
46	hoed	hat	5.39	1.4914
47	hout	wood	5.41	1.6812
48	kam	comb	5.34	0
49	kano	canoe	8.52	0.4771
50	kapstok	coat rack	5.72	0.699
51	kar	cart	5.26	1.0414
52	kermis	fair	5.21	1
53	kers	cherry	5.74	0
54	keuken	kitchen	5.04	1.9542
55	knie	knee	4.66	1.3617
56	koelkast	fridge	6.44	0.8451
57	koffer	suitcase	6.28	1.3979
58	kok	chef	6.47	0.6021
59	kraan	tap	5.65	1
60	krant	newspaper	5.89	1.8573
61	kring	circle	5.21	1.6812
62	kroon	crown	5.56	1.3617
63	kussen	pillow	5.04	1.2041
64	kwast	brush	8.01	0.6021
65	laars	boot	6.03	0.6021
66	leeuw	lion	5.16	1.1761
67	lepel	spoon	4.19	1.0414
68	markt	market	6.31	1.7853
69	masker	mask	5.34	1.1461
70	mes	knife	4.8	1.5185
71	pan	pan	5.21	1.3802
72	pen	pen	5.73	1.2041
73	pijl	arrow	5.6	0.9542
74	pil	pill	5.84	1.0792
75	pit	pit	6.9	0.4771
76	plafond	ceiling	6.41	1.3802
77	plank	shelf	6.08	1.1461
78	pleister	plaster	6.02	0.699
79	poot	paw	4.96	1.0792
80	potlood	pencil	4.76	1
81	put	put	5.13	0.9542
82	riem	belt	6.87	1.1139
83	ring	ring	5.25	1.3802
84	rok	skirt	5.63	1.3222
85	rolstoel	wheelchair	7.05	0.7782
86	roos	rose	6.01	1.1461

Item	Noun	Translation	Age of Acquisition	Lexeme frequency
87	schaar	scissors	5.03	0.699
88	schaats	skate	7.34	0
89	schep	shovel	5.66	0
90	schildpad	turtle	5.65	0.6021
91	schommel	swing	4.59	0.301
92	schoorsteen	chimney	6.35	0.9031
93	schrift	notebook	6.15	0.8451
94	schroef	screw	8.55	0.301
95	sigaar	cigar	9.03	1.2553
96	slang	snake	5.66	1.2553
97	slee	sleigh	5.36	0.301
98	sleutel	key	5.41	1.5441
99	snavel	beak	7.03	0.9542
100	sneeuw	snow	4.26	1.5911
101	spijker	nail	7.04	0.699
102	spons	sponge	6.09	0.6021
103	spook	ghost	5.17	0.8451
104	stempel	stamp	6.21	1.0792
105	stok	stick	4.92	1.3617
106	strik	bow	5.8	0.301
107	stropdas	tie	8.08	0.7782
108	stuur	steering wheel	5.6	1.3979
109	taart	cake	6.11	0.9031
110	tafel	table	4.03	2.2765
111	tak	branch	5.53	1.2553
112	tank	tank	7.47	0.8451
113	tas	bag	5.37	1.5051
114	taxi	taxi	7.84	1.415
115	tegel	tile	7.04	0
116	thee	tea	6.62	1.7076
117	tijger	tiger	6.21	0.699
118	toren	tower	5.38	1.3222
119	touw	rope	5.54	1.3979
120	traan	tear	5.08	0.6021
121	trommel	drum	5.53	1.1461
122	tulp	tulip	7.13	0
123	uil	owl	6.4	0.699
124	vaas	vase	5.47	0.8451
125	varken	pig	4.6	1
126	veter	lace	5.38	0
127	vlag	flag	6.64	1.2553
128	vlam	flame	6.65	1.0792
129	vlek	stain	5.45	1.0414
130	vlieg	fly	4.78	0.9542
131	vlieger	kite	6	0.4771
132	voet	foot	4.11	1.9823

Item	Noun	Translation	Age of Acquisition	Lexeme frequency
133	weegschaal	scale	7.14	0.6021
134	wieg	cradle	5.7	1
135	wijn	wine	7.31	2.1492
136	wol	wool	5.59	1
137	wolk	cloud	5.58	1.1761
138	worm	worm	5.58	0.4771
139	zandbak	sandbox	4.88	0.301
140	zwembad	swimming pool	5.5	1.1461

Appendix 3

to Chapters 2, 3 and 4

List 1 of items used in the nonword reading task and the nonword repetition task.

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
1	dukker	dY+'k@r	5	4386	1.85
2	hatig	ha't@x	5	4514	1.91
3	bletto	blE+'to	5	4335	1.96
4	kreffie	krE+'fi	5	3812	2.09
5	tazig	ta'z@x	5	3930	1.17
6	tiera	ti'ra	4	3492	2.73
7	jatta	jA+'ta	4	3484	1.48
8	lielee	li'le	4	3356	2.6
9	zaffer	zA+'f@r	5	2920	1.85
10	geso	Ge'so	4	2929	2.17
11	bova	bo'va	4	2933	1.43
12	bessee	bE'se	4	2735	2.13
13	werler	wEr'l@r	6	2614	2.3
14	lettuu	lE'ty	4	2532	1.79
15	krejo	kre'jo	5	2806	1.75
16	losies	lo'sis	5	2429	2.21
17	rada	ra'da	4	2409	1.61
18	kaba	ka'ba	4	2373	1.39
19	reffe	rE+'f@	4	2558	2.14
20	kogie	ko'Gi	4	2233	1.83
21	bipper	bI'p@r	5	2293	1.73
22	blebo	ble'bo	5	2140	1.82
23	trassa	trA+'sa	5	2079	1.59
24	giddo	GI'do	4	2071	1.49
25	worwee	wOr'we	5	2001	1.92
26	eppar	E'pAr	4	1913	1.48
27	butting	bY+'tIN	5	1860	1.93
28	keking	ke'kIN	5	1922	2.03
29	tovie	to'vi	4	1891	1.7
30	weppie	wE'pi	4	1879	1.97
31	steddert	stE'd@rt	7	1819	2.14
32	eugee	2'Ge	3	1720	1.69
33	peger	pe'G@r	5	1626	2.29
34	bruffa	brY+'fa	5	1591	1.66
35	kieha	ki'ha	4	1598	1.82
36	widdel	wI'd@l	5	1559	1.91
37	rowa	ro'wa	4	1562	1.29
38	sprokel	spro'k@l	7	1521	1.96
39	seza	se'za	4	1459	1.52
40	sieters	si't@rs	6	1450	2.38

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
41	dofor	do'fOr	5	1362	1.44
42	bachal	bA'xAl	5	1353	1.79
43	leuvo	l2'vo	4	1327	1.5
44	hekers	he'k@rs	6	1336	2.19
45	rubbee	rY'be	4	1285	1.72
46	baho	ba'ho	4	1211	1.34
47	kekkie	kE'ki	4	1203	2.12
48	weelsel	wel's@l	6	1140	2.39
49	stetes	ste't@s	6	1131	2.32
50	joten	jo't@n	5	1104	1.57
51	fievet	fi'v@t	5	1044	1.71
52	boepel	bu'p@l	5	1017	2.17
53	despro	dE'spro	6	926	2.03
54	hustig	hY+s't@G	6	957	1.55
55	valijks	va'l@ks	6	965	1.19
56	herdra	hEr'dra	6	953	2.01
57	brering	bre'rIn	6	914	2.37
58	laggels	lA'G@ls	6	831	1.87
59	hobu	ho'by	4	866	1.48
60	teurvert	t2r'v@rt	7	877	1.84
61	dibbel	dI'b@l	5	872	1.88
62	dreppu	drE+'py	5	808	1.8
63	vogers	vo'G@rs	6	840	2.08
64	seggo	sE'Go	4	813	1.44
65	loddels	lO'd@ls	6	779	2.02
66	retsing	rE+t'sIN	6	771	2.02
67	sliffo	slI'fo	5	774	1.44
68	halkong	hAl'kON	6	772	1.67
69	dufers	dy'f@rs	6	717	1.87
70	jotties	jO'tis	5	708	2.15
71	ludecht	ly'd@xt	6	695	1.55
72	bruddes	brY'd@s	6	714	1.99
73	harwoor	hAr'wor	6	711	1.7
74	hochtel	hox't@l	6	667	2.18
75	vrebber	vrE+'b@r	6	652	2.14
76	heggel	hE'G@l	5	644	2.02
77	vasser	vA's@r	5	648	1.95
78	sochie	sO'xi	4	584	2.01
79	wozes	wo'z@s	5	620	1.66
80	lillig	lI'l@x	5	606	1.52
81	grebbur	GrE+'bYr	6	605	1.94
82	drozer	dro'z@r	6	590	1.87
83	farel	fa'r@l	5	592	2.27
84	zoeres	zu'r@s	5	569	2.54
85	kluttert	klY+'t@rt	7	555	1.93
86	drachis	dra'xIs	6	571	1.82

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
87	kattus	kA'tYs	5	558	1.6
88	ochtro	Ox'tro	5	543	1.86
89	hokkee	hO'ke	4	548	1.92
90	rekkul	rE'kYl	5	526	1.6
91	dangel	dA'N@l	5	515	1.95
92	bropers	bro'p@rs	7	520	2.03
93	gredis	Gre'dIs	6	527	1.67
94	stoju	sto'jy	5	479	1.48
95	voebert	vu'b@rt	6	473	2.09
96	scheestie	sxe'sti	6	467	2.26
97	buurling	byr'lINs	6	472	1.82
98	eftoos	Ef'tos	5	468	1.63
99	strewels	stre'w@ls	8	452	2.18
100	zonger	zO'N@r	5	424	2.11
101	strabeel	stra'bel	7	447	2.19
102	slosers	slo's@rs	7	429	2.02
103	sprefel	spre'f@l	7	418	2.16
104	schikkor	sxI'kOr	6	409	1.79
105	parchoe	pAr'xu	5	425	1.78
106	sojoe	so'ju	4	423	1.64
107	laasblie	las'bli	6	378	1.74
108	buwing	by'wIN	5	393	1.71
109	spurrig	spY'r@x	6	384	1.43
110	veddelt	vE'd@lt	6	383	1.98
111	brases	bra's@s	6	374	2.25
112	fabru	fA+'bry	5	373	1.66
113	zwezoe	zwe'zu	5	352	1.59
114	kaatscha	kat'sxa	6	364	1.68
115	rattels	rA't@ls	6	362	2.39
116	kosves	kOs'v@s	6	365	1.81
117	kluwach	kly'wAx	6	362	1.54
118	friekelt	fri'k@lt	7	360	2.01
119	gratur	Gra'tYr	6	341	1.87
120	toddings	tO'dINs	6	352	1.68
121	vrefelt	vre'f@lt	7	344	2.05
122	kravel	kra'v@l	6	339	1.98
123	rupels	ry'p@ls	6	334	1.94
124	kikkels	kI'k@ls	6	314	2.02
125	drewer	dre'w@r	6	323	2.25
126	oosbree	os'bre	5	309	2
127	joefra	ju'fra	5	292	1.96
128	raalkro	ral'kro	6	308	1.74
129	storcho	stOr'xo	6	314	2.02
130	kladoe	kla'du	5	302	1.6
131	woorgra	wor'Gra	6	303	1.74
132	borkos	bOr'kOs	6	295	1.71

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
133	plaffoe	plA'fu	5	289	1.57
134	klegies	kle'Gis	6	295	2.13
135	vorlers	vOr'l@rs	7	275	2.16
136	dwezies	dwe'zis	6	273	1.88
137	spiebor	spi'bOr	6	261	2.02
138	plenges	plE'N@s	6	257	2.02
139	pilloch	pI'lOx	5	269	1.57
140	sibbies	sI'bis	5	262	1.91

List 2 of items used in the nonword reading task and the nonword repetition task.

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
1	dulling	dY+'lIN	5	4360	1.78
2	haro	ha'ro	4	4676	1.98
3	blekker	blE+'k@r	6	4304	2.19
4	tafie	ta'fi	4	3812	1.38
5	jallee	jA+'le	4	3424	1.77
6	lieva	li'va	4	3160	2.04
7	zasso	zA+'so	4	2939	1.59
8	bojo	bo'jo	4	2975	1.48
9	bettu	bE'ty	4	2617	2.03
10	wersee	wEr'se	5	2700	2.38
11	leller	lE'l@r	5	2565	2.65
12	krefer	kre'f@r	6	2617	2.25
13	loda	lo'da	4	2419	1.27
14	rasies	ra'sis	5	2419	2.44
15	kabo	ka'bo	4	2251	1.48
16	rebba	rE+'ba	4	2360	1.86
17	kosa	ko'sa	4	2183	1.66
18	biffe	bI'f@	4	2505	1.53
19	blepper	ble'p@r	6	2248	1.87
20	traggie	trA+'Gi	5	2128	1.84
21	gippar	GI'pAr	5	1964	1.27
22	worvie	wOr'vi	5	1975	1.84
23	ekking	E'kIN	4	1958	1.97
24	buddo	bY+'do	4	1993	1.64
25	kedert	ke'd@rt	6	1852	2.22
26	wetting	wE'tIN	5	1820	2.02
27	steddig	stE'd@x	5	1794	1.81
28	wapie	wa'pi	4	1836	1.73
29	euvie	2'vi	3	1810	1.78
30	bruddel	brY+'d@l	6	1583	2.12
31	kieger	ki'G@r	5	1608	2.24
32	wiffa	wI'fa	4	1567	1.43
33	rogee	ro'Ge	4	1654	1.96

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
34	sakel	sa'k@l	5	1545	1.98
35	sproza	spro'za	6	1463	1.34
36	sewa	se'wa	4	1528	1.39
37	siefor	si'fOr	5	1407	2.07
38	dokers	do'k@rs	6	1349	2.04
39	batters	bA't@rs	6	1396	2.13
40	leubee	l2'be	4	1309	1.85
41	hevo	he'vo	4	1324	1.66
42	ruchal	rY'xAl	5	1327	1.82
43	bastu	ba'sty	5	1236	1.83
44	kettes	kE't@s	5	1190	2.33
45	hassel	hA+'s@l	5	1165	2.21
46	weelkie	wel'ki	5	1175	2.21
47	steho	ste'ho	5	1117	1.69
48	jovet	jo'v@t	5	1077	1.72
49	fiepel	fi'p@l	5	1032	2
50	boebel	bu'b@l	5	955	2.19
51	detten	dE't@n	5	1048	1.98
52	vadra	va'dra	5	979	1.64
53	boggo	bO'Go	4	864	1.35
54	hersu	hEr'sy	5	911	2.08
55	brevert	bre'v@rt	7	899	2.24
56	larring	lA'rIn	5	906	1.86
57	hollijks	ho'l@ks	6	918	1.27
58	teurbu	t2r'by	5	862	1.58
59	dippu	dI'py	4	810	1.3
60	dreggers	drE+'G@rs	7	844	2.11
61	votrie	vo'tri	5	795	1.79
62	seddels	sE'd@ls	6	801	2.1
63	berfo	bEr'fo	5	791	1.97
64	lokkong	lO'kON	5	783	1.69
65	rethus	rE+t'hY+s	6	790	1.5
66	chrosing	xro'sIN	6	766	1.97
67	halkes	hAl'k@s	6	767	1.95
68	dudecht	dy'd@xt	6	716	1.62
69	joddes	jO'd@s	5	723	1.93
70	luwoor	ly'wor	5	723	1.6
71	brutties	brY'tis	6	699	1.97
72	harfers	hAr'f@rs	7	684	2.01
73	vrettel	vrE+'t@l	6	662	2.21
74	hesche	hE'sx@	4	628	2.25
75	vabbur	vA'bYr	5	627	1.5
76	tuzes	ty'z@s	5	624	1.59
77	sollig	sO'l@x	5	608	1.55
78	wogu	wo'Gy	4	632	1.29
79	lirrel	lI'r@l	5	601	2.04

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
80	gresser	GrE+'s@r	6	626	2.38
81	drores	dro'r@s	6	582	2.38
82	fasoe	fa'su	4	585	1.79
83	schazer	sxa'z@r	6	584	1.9
84	zoechis	zu'xIs	5	575	1.6
85	kluchie	klY+'xi	5	558	1.9
86	dratert	dra't@rt	7	553	2.19
87	katro	kA'tro	5	543	1.75
88	ochtus	Ox'tYs	5	558	1.46
89	hongel	hO'N@l	5	525	2.09
90	rekkee	rE'ke	4	542	2.23
91	dakkul	dA'kYl	5	521	1.35
92	brovits	bro'vIts	7	523	1.38
93	grevoe	Gre'vu	5	481	1.98
94	kudis	ky'dIs	5	526	1.35
95	bloetoos	blu'tos	6	486	1.86
96	stobert	sto'b@rt	7	474	1.97
97	burwo	bYr'wo	5	466	1.47
98	schelu	sxe'ly	5	467	2.19
99	efscho	Ef'sxo	5	469	1.74
100	streenger	stre'N@r	7	428	2.22
101	zossers	zO's@rs	6	436	2.08
102	strawels	stra'w@ls	8	442	2.11
103	slobeel	slo'bel	6	446	1.85
104	spredings	spre'dINs	8	388	1.77
105	schiffel	sxI'f@l	6	412	1.99
106	laasjoe	las'ju	5	421	1.68
107	bublie	by'bli	5	374	1.9
108	spukkor	spY'kOr	6	399	1.66
109	verrig	vE'r@x	5	384	1.92
110	brawing	bra'wIN	6	390	1.99
111	fasses	fA+'s@s	5	371	2.02
112	zwedelt	zwe'd@lt	7	377	1.92
113	kaatwach	kat'wAx	6	368	1.49
114	rarrelt	rA'r@lt	6	358	2.28
115	koskelt	kOs'k@lt	7	362	2
116	klujer	kly'j@r	6	324	1.56
117	sukra	sy'kra	5	338	1.63
118	frieves	fri'v@s	6	363	2.02
119	grawer	Gra'w@r	6	339	2.2
120	tottur	tO'tYr	5	340	1.66
121	krapels	kra'p@ls	7	335	1.96
122	ruvel	ry'v@l	5	338	1.95
123	fobree	fo'bre	5	316	2.07
124	kiffelt	kI'f@lt	6	333	1.89
125	drekels	dre'k@ls	7	312	2.21

Item	Nonword	Transcription	Phonemes	Syllable frequency	Bigram frequency
126	ooskro	os'kro	5	313	1.72
127	joegra	ju'Gra	5	308	1.96
128	raalbru	ral'bry	6	336	1.77
129	stordoe	stOr'du	6	303	1.73
130	klaacho	kla'xo	5	313	1.73
131	woorzies	wor'zis	6	291	1.84
132	borgies	bOr'Gis	6	299	2.02
133	plakkos	plA'kOs	6	295	1.67
134	klefra	kle'fra	6	283	1.9
135	deunges	d2'N@s	5	263	1.95
136	dwefoe	dwe'fu	5	271	1.7
137	spiebra	spi'bra	6	262	2.09
138	plebbies	plE'bis	6	262	1.93
139	pibbor	pI'bOr	5	257	1.59
140	sillers	sI'l@rs	6	263	1.99

Appendix 4

to Chapters 2 and 3

The cluster statistic, standard deviation and confidence interval range of all EEG results of the younger adults reported on in Chapters 2 and 3.

Comparison	Analysis	Time domain	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lemma retrieval						
1st vs 5th item in ordinal position	Stimulus-locked	100 – 265 ms	< .001	-1505.0	< .001	< .001
	Response-locked	-445 – -195 ms	.005	-2836.6	< .001	.002
Lexeme retrieval						
AoA ca. 5 years vs ca. 6 years	Stimulus-locked	100 – 300 ms	.002	1116.1	< .001	.001
AoA ca. 5 years vs ca. 7 years	Response-locked	-475 – -330 ms	< .001	-1954.7	< .001	< .001
Phonological encoding in reading						
Length 4 vs 5 phonemes	Stimulus-locked	350 – 415 ms	.003	665.8	< .001	.002
	Response-locked	-335 – -320 ms	.008	200.7	.001	.002
Length 4 vs 6 phonemes	Stimulus-locked	390 – 425 ms	.005	317.9	< .001	.002
	Response-locked	-330 – -320 ms	.008	117.0	.001	.002
Phonological encoding in repetition						
Length 4 vs 5 phonemes	Stimulus-locked	350 – 410 ms	.006	-321.6	.001	.002
		530 – 610 ms	.001	-830.7	<.001	<.001
		650 – 750 ms	<.001	-872.4	<.001	<.001
	Response-locked	-580 – - 545 ms	.016	-201.8	.002	.004
Length 4 vs 6 phonemes	Stimulus-locked	935 – 1020 ms	.002	981.7	<.001	.001
Phonetic encoding in reading						
High vs moderate frequency	Stimulus-locked	400 – 450 ms	.020	316.5	.002	.004
High vs low frequency	Stimulus-locked	350 – 450 ms	.012	665.4	.002	.003
	Response-locked	-250 – -200 ms	.021	214.7	.002	.004
Phonetic encoding in repetition						
High vs moderate frequency	Stimulus-locked	475 – 675 ms	.003	1635.6	< .001	.002
High vs low frequency	Stimulus-locked	350 – 375 ms	.020	-136.5	.002	.004

Appendix 5

to Chapter 3

The cluster statistic, standard deviation and confidence interval range of all EEG results of the older adults reported on in Chapter 3.

Comparison	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lemma retrieval						
1st vs 5th item in ordinal position	Response-locked	-540 – -450 ms	.006	-340.9	.004	.007
Lexeme retrieval						
AoA ca. 5 vs ca. 6 years	Response-locked	-430 – -420 ms	.012	-78.8	.002	.003
		-210 – -195 ms	.009	-96.7	.001	.003
		-165 – -140 ms	.013	-131.6	.002	.003
Phonological encoding in reading						
Length 4 vs 6 phonemes	Stimulus-locked	100 – 135 ms	.020	124.7	.002	.004
		280 – 300 ms	.004	186.8	< .001	.002
Phonetic encoding in reading						
High vs moderate frequency	Stimulus-locked	280 – 300 ms	.009	142.7	.001	.003
		365 – 375 ms	.022	46.5	.002	.004
High vs low frequency	Stimulus-locked	280 – 290 ms	.020	59.2	.002	.004
		420 – 455 ms	.008	174.2	.001	.002
	Response-locked	-455 – -435 ms	.016	98.6	.002	.004

Appendix 6

to Chapter 3

The cluster statistic, standard deviation and confidence interval range of all EEG results of the comparison of the older adults and younger adults reported on in Chapter 3.

Condition	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lemma retrieval						
5th item in ordinal position	Stimulus locked	100 – 265 ms	.003	907.6	< .001	.001
			.002	-1088.3	< .001	.001
	Response-locked	-540 – -450 ms	.023	255.8	.002	.004
			.013	-436.6	.002	.003
		-445 – -195 ms	.004	-2139.8	< .001	.002
Lexeme retrieval						
AoA ca. 6 years	Stimulus-locked	100 – 300 ms	.002	-1749.4	< .001	.001
Phonological encoding in reading						
5 phonemes	Stimulus-locked	350 – 415 ms	.015	-386.5	.002	.003
6 phonemes	Stimulus-locked	390 – 425 ms	.014	-227.5	.002	.003
Phonetic encoding in reading						
Moderate frequency	Stimulus-locked	280 – 375 ms	.007	-683.6	.001	.002
Low frequency	Stimulus-locked	280 – 455 ms	.011	-904.9	.002	.003

Appendix 7

to Chapter 4

Time post onset in months, c-scores on the subtests Naming, Reading and Repetition of the CAT, or severity grades on the subtests Naming and Repetition on the AAT, and scores on PALPA 7 (repetition of words) and PALPA 8 (repetition of nonwords) of the aphasic speakers. ° = severity grades on the AAT: 3 is a severe disorder, 4 is an average disorder. * = within one standard deviation of the NBD mean score (PALPA 7: M = 24, SD = 0; PALPA 8: M = 29.25, SD=1.3).

Participant	Post onset	AT Naming	CAT Reading	AT Repetition	PALPA 7: words	PALPA 8: nonwords
Phonological encoding disorder						
1	6	7	6	5	24*	28*
2	4	5	4	5	18	21
3	5	4	4	4	23	12
4	3	8	6	6	23	25
5	9	3	4	3	12	3
AoS						
6	5	6	5	5	19	15
7	4	4	4	3	17	5
8	2	3	4	3	15	15
9	3	5	4	4	23	23
10	7	6	6	4	21	17
11	2	7	6	5	24*	26
12	5	3	4	3	6	12
13	123	5°	n.a.	5°	22	19
14	5	8	6	5	24*	20
15	70	4°	n.a.	3°	20	2
16	122	8°	n.a.	8°	22	23

Appendix 8

to Chapter 4

DIAS (Feiken & Jonkers, 2012) scores of the individuals with AoS on four tasks: articulatory control, articulation of phonemes, diadochokinesis and articulation of words. Column 'S' shows the severity score per task followed by the severity grade (severe, moderate, mild, none). Column 'A+B' provides the sum score of the occurrence of two characteristics: (A) response improved when imitating the assessor and (B) groping. The columns with numbers correspond to the characteristics of AoS observed in the task: (1) inconsistent production of the same phoneme, (2) production of consonants worse than production of vowels, (3) worse performance on alternating syllable strings, (4) groping, (5) initiation problems, (6) segmentation of syllables, (7) segmentation of clusters and (8) effect of articulatory complexity. The characteristics score in the numbered columns is followed by the indication whether the characteristic was present. Groping (4) does not have a characteristics score.

	Articulatory control		Articulation of phonemes			Diadochokinesis			Articulation of words				
Participant	S	A+B	S	1	2	S	3	4	S	5	6	7	8
6	20	3	26	0	-2	15	0.4		208	0.73	1	0	0
	severe	yes	mild	no	no	severe	yes	yes	mild	yes	yes	no	no
7	17	13	17	0	3	9	0.73		183	0.18	0.5	0	-2
	severe	yes	severe	no	yes	severe	no	no	moderate	yes	yes	no	no
8	26	5	16	0	12	7	0.19		164	0.45	1	0	3.67
	mild	yes	severe	no	yes	severe	yes	yes	moderate	yes	yes	no	yes
9	28	2	28	0	2	32	0.65		204	1	0.67	0	6.67
	mild	no	mild	no	no	mild	yes	yes	mild	yes	yes	no	yes
10	22	7	26	1	-4	125	0.86		256	0.27	0.17	0.4	0.67
	severe	yes	mild	no	no	none	no	yes	none	yes	yes	yes	no
11	25	5	27	1	3	16	0.39		199	0.18	0.17	0	-1.34
	mild	yes	mild	no	yes	severe	yes	no	mild	yes	yes	no	no
12	30	0	30	0	0	115	0.06		191	0.6	0.6	0.6	3
	none	no	none	no	no	none	yes	yes	mild	yes	yes	yes	yes
13	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
14	22	7	24	4	4	64	0.68		201	0.2	0	0.2	2.34
	severe	yes	moderate	yes	yes	moderate	yes	yes	mild	no	no	yes	yes
15	21	5	26	0	2	28	0.31		186	0.27	0.83	0	2.7
	severe	yes	mild	no	no	mild	yes	no	moderate	yes	yes	no	yes
16	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Appendix 9

to Chapter 4

Behavioral results of the aphasic speakers on the two naming tasks and the nonword reading task reported on in Chapter 4. The last row shows the average score and the standard deviation of the NBDs. * = within 1 standard deviation of the NBDs.

Participant	**Score naming task 1** targets lemma retrieval maximum score = 125	**Score naming task 2** targets lexeme retrieval maximum score = 140	**Score nonword reading task** targets phonological and phonetic encoding maximum score = 140
Phonological encoding disorder			
1	105	127*	133*
2	84	100	73
3	32	34	18
4	108*	124*	132*
5	21	9	0
AoS			
6	61	82	71
7	48	40	21
8	18	33	33
9	81	80	76
10	105	105	104
11	91	106	73
12	29	32	29
13	83	85	0
14	87	103	77
15	79	78	20
16	107*	105	71
NBDs	113 (sd=6)	127 (sd=17)	134 (sd=4)

Appendix 10

to Chapter 4

The cluster statistic, standard deviation and confidence interval range of all EEG results for individuals with a phonological encoding disorder reported on in Chapter 4.

Comparison	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lexeme retrieval						
AoA ca. 5 vs ca. 6 years	Stimulus-locked	140 – 155 ms	< .001	231.1	< .001	< .001
	Response-locked	-535 – -445 ms	< .001	823.0	< .001	< .001
		-410 – -355 ms	< .001	522.7	< .001	< .001
AoA ca. 5 vs ca. 7 years	Stimulus-locked	475 – 530 ms	< .001	-419.0	< .001	< .001
		545 – 570 ms	< .001	-177.2	< .001	< .001
	Response-locked	-570 – -550 ms	< .001	-208.6	< .001	< .001
Phonetic encoding in reading						
High vs moderate frequency	Response-locked	-385 – -170 ms	< .001	6331.0	< .001	< .001
High vs low frequency	Stimulus-locked	410 – 500 ms	< .001	-925.7	< .001	< .001

Appendix 11

to Chapter 4

The cluster statistic, standard deviation and confidence interval range of all EEG results for individuals with AoS reported on in Chapter 4.

Comparison	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lexeme retrieval						
AoA ca. 5 vs ca. 6 years	Stimulus-locked	225 – 335 ms	.012	893.7	.002	.003
Phonological encoding in reading						
Length 4 vs 5 phonemes	Stimulus-locked	280 – 305 ms	.006	521.9	.001	.002

Appendix 12

to Chapter 4

The cluster statistic, standard deviation and confidence interval range of all EEG results for individuals with a phonological encoding disorder (Phonol. enc. dis.) and individuals with AoS compared to NBDs and the comparison of the difference between individuals with a phonological encoding disorder and NBDs (Phonol. enc. dis. vs. NBD) to the difference between individuals with AoS and NBDs (AoS vs. NBD) reported on in Chapter 4.

Comparison	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lemma retrieval						
Phonol. enc. dis. vs. NBD						
Items in fifth ordinal position	Stimulus-locked	130 – 175 ms	< .001	981.1	< .001	< .001
		290 – 445 ms	< .001	2239.5	< .001	<.001
	Response-locked	-600 – -575 ms	< .001	162.8	< .001	< .001
		-565 – -500 ms	.006	346.2	.001	.002
		-190 – -165 ms	.006	176.9	.001	.002

Comparison	Analysis	Time window	Probability	Cluster statistics	Standard deviation	Confidence interval range
Lexeme retrieval						
Phonol. enc. dis. vs. NBD						
AoA of ca. 6 years	Stimulus-locked	295 – 520 ms	.005	2608.2	< .001	.002
	Response-locked	-600 – -335 ms	< .001	5101.9	< .001	<. 001
AoA of ca. 7 years	Stimulus-locked	320 – 500 ms	.002	1864.2	< .001	.001
	Response-locked	-390 – -290 ms	.003	1338.8	< .001	.002
AoS vs. NBD						
AoA of ca. 6 years	Stimulus-locked	360 – 525 ms	.022	1649.7	.002	.004
Phonological encoding in reading						
Phonol. enc. dis. vs. NBD						
5 phonemes	Response-locked	-500 – -210 ms	< .001	6201	< .001	< .001
6 phonemes	Stimulus-locked	130 – 180 ms	.006	769.9	< .001	.002
AoS vs. NBD						
5 phonemes	Stimulus-locked	195 – 235 ms	.018	-394.1	.002	.004
	Response-locked	-350 – -100 ms	.006	4296.4	.001	.002
6 phonemes	Stimulus-locked	140 – 280 ms	.022	-957.2	.002	.004
Phonetic encoding in reading						
Phonol. enc. dis. vs. NBD						
Moderate syllable frequency	Stimulus-locked	390 – 500 ms	.004	2364.2	< .001	.002
	Response-locked	-355 – -325 ms	.011	719.3	.002	.003
Low syllable frequency	Stimulus-locked	130 – 190 ms	.004	1155.3	< .001	.002
AoS vs. NBD						
Moderate syllable frequency	Response-locked	-275 – -100 ms	.016	2474.7	.002	.004
(Phonol. enc. dis. vs. NBD) vs. (AoS vs. NBD)						
Moderate syllable frequency	Stimulus-locked	430 – 500 ms	.013	-1008.4	.002	.003

Summary

Distinguishing a phonological encoding disorder from Apraxia of Speech in individuals with aphasia by using EEG

As we speak, lemma retrieval, lexeme retrieval, phonological encoding and phonetic encoding take place before articulation. These stages can be independently impaired. Individuals with aphasia can have an impairment at the first three stages, and individuals with Apraxia of Speech at the level of phonetic encoding (although they may also have co-occurring aphasia). This project studied whether EEG can be used to differentiate a phonological encoding disorder from Apraxia of Speech as current methods are not optimal. A protocol was developed to trace the speech production stages, and tested in younger adults (Chapter 2), older adults (Chapter 3) and individuals with aphasia and a phonological encoding disorder and individuals with aphasia and Apraxia of Speech (Chapter 4).

Chapter 1 describes relevant background literature on theoretical and methodological issues and discusses the four characteristics that we used to identify levels of processing:
1. Lemma retrieval - The cumulative semantic interference effect
2. Lexeme retrieval - an effect of Age of Acquisition
3. Phonological encoding - an effect of length in phonemes on nonword production.
4. Phonetic encoding - an effect of syllable frequency.

Chapter 2 describes the protocol (picture naming and nonword reading/repetition tasks) and the results of testing this in a group of young adults. As planned, Characteristics 1 and 2 (above) were found in the response times and in the EEG data of picture naming tasks, indicating that the protocol could identify the stages of lemma and lexeme retrieval. Characteristics 3 and 4 were found in the response times and in the EEG data of the nonword reading task, identifying the phonological and phonetic encoding stages. This was not the case in the repetition task, so this task was removed from the protocol.

In *Chapter 3* the protocol was tested in older adults and also identified all four speech production stages. Although compared to the younger adults, the older adults required more time to respond, the duration of the stages was not increased in the EEG data. The scalp distributions of the effects that were used to track the stages were comparable but the time window and the neurophysiological signature of the stages differed between younger and older adults, suggesting that the efficiency of the neural networks involved in these stages decreased with age.

In *Chapter 4* the stages were studied in the individuals with aphasia and a phonological encoding disorder and in the individuals with aphasia and Apraxia of Speech. Manipulations of impaired stages could not be identified in the EEG data and it was not possible to differentiate a phonological encoding disorder from Apraxia of Speech, nor was it possible to differentiate when comparing to matched non-brain-damaged individuals: both groups differed in phonetic encoding, but individuals with aphasia also differed in phonological encoding. However, the protocol could differentiate the disorders due to differences between the groups in the EEG data (relative to non-brain-damaged individuals) in the phonetic encoding stage only.

Chapter 5 provides a general discussion on the findings and recommendations for future research.

Samenvatting

Een stoornis in fonologisch coderen van spraakapraxie onderscheiden in personen met afasie door middel van EEG

Als we spreken vinden er verschillende processen in onze hersenen plaats. We moeten eerst het woord vinden en bedenken hoeveel en welke spraakklanken we nodig hebben. Daarna moeten we de bijbehorende spraakklanken vinden en deze in de juiste volgorde zetten. Tenslotte moeten we plannen hoe we onze mond, tong, kaak en strottenhoofd moeten bewegen om deze spraakklanken uiteindelijk te articuleren terwijl we uitademen. Na een beroerte kan er een stoornis optreden in deze processen. Een stoornis in het vinden van het woord of een stoornis met de spraakklanken kan voorkomen bij personen met afasie, een taalstoornis die optreedt als gevolg van focale hersenschade nadat de taalverwerving is afgerond. Een stoornis in het plannen van de bewegingen voor de spraak wordt spraakapraxie genoemd. Sommige kenmerken die kunnen voorkomen in de spraak van personen met spraakapraxie kunnen ook geobserveerd worden in de spraak van personen met een stoornis in het vinden en ordenen van spraakklanken, oftewel een stoornis in fonologisch coderen. Een voorbeeld van zo'n kenmerk is dat deze patiënten meer fouten maken in woorden die moeilijk uit te spreken zijn, zoals 'herfst'. Dit maakt het lastig om een stoornis in fonologisch coderen te onderscheiden van spraakapraxie. Ook de locatie van het hersenletsel kan niet gebruikt worden om deze twee stoornissen van elkaar te onderscheiden, omdat sommige gebieden in de hersenen, zoals het gebied van Broca, in personen met een afasie en in personen met spraakapraxie beschadigd kunnen zijn. Verder komen een stoornis in fonologisch coderen en spraakapraxie zelden alleen voor: ze komen meestal in combinatie met afasie voor. Aangezien bestaande methodes niet optimaal zijn om een stoornis in fonologisch coderen en spraakapraxie van elkaar te onderscheiden in personen met afasie, heb ik in dit proefschrift onderzocht of EEG, het meten van kleine veranderingen in electrische hersenactiviteit met electroden die op de hoofdhuid geplaatst worden, hiervoor gebruikt kan worden. Daarom heb ik een protocol ontwikkeld, waarin de verschillende processen van het spreken getraceerd worden. Ik heb dit protocol getest in jongere volwassenen (Hoofdstuk 2), in oudere volwassenen (Hoofdstuk 3) en daarna in personen met afasie en een stoornis in fonologisch coderen en in personen met afasie en spraakapraxie (Hoofdstuk 4).

In *Hoofdstuk 1* beschreef ik de processen die plaatsvinden tijdens het spreken en welke taalkundige kenmerken invloed hebben op die processen. Ik ging dieper in op de vier kenmerken waarmee ik mijn items manipuleerde in de taken van het protocol.
1. Als je het woord 'spin' wilt vinden, dan heb je daar meer tijd voor nodig als je vlak daarvoor andere insecten hebt benoemd.

2. Bedenken hoeveel en welke spraakklanken je voor het woord nodig hebt kost meer tijd voor woorden die je op een latere leeftijd geleerd hebt, zoals 'anker', dan voor eerder geleerde woorden, zoals 'boek'.
3. Het vinden en ordenen van spraakklanken duurt langer voor woorden die uit meer spraakklanken bestaan.
4. Voor lettergrepen die je vaak gebruikt kun je de bewegingen voor de spraak sneller plannen dan voor lettergrepen die je weinig gebruikt.

We legden uit hoe EEG werkt en hebben experimenten besproken waarin EEG gebruikt werd om de taalkundige kenmerken die invloed hebben op de processen van spreken te bestuderen. In het tweede deel van de inleiding beschreef ik de kenmerken die in de spraak van personen met spraakapraxie en personen met een stoornis in fonologisch coderen kunnen voorkomen en de gebieden waarin hersenletsel geobserveerd kan worden in beide stoornissen, waardoor de stoornissen lastig van elkaar te onderscheiden zijn in personen met afasie.

In *Hoofdstuk 2* werd het protocol beschreven en getest in een groep jonge volwassenen. Het protocol bestaat uit twee benoemtaken met afbeeldingen die gemanipuleerd zijn met de hierboven genoemde kenmerken 1 en 2. Verder bevat het protocol een leestaak en een herhaaltaak met nonwoorden - betekenisloze combinaties van letters die op woorden lijken - die gemanipuleerd zijn met kenmerken 3 en 4. Dit was het eerste EEG onderzoek waarin alle processen van het spreken werden onderzocht in dezelfde groep deelnemers. Ik vond kenmerken 1 en 2 in de reactietijden en in de EEG data, dus zowel het proces van vinden van het woord als het proces van bedenken van hoeveel en welke spraakklanken benodigd zijn konden getraceerd worden. Kenmerken 3 en 4 vond ik in de reactietijden en in de EEG data van de leestaak, dus ook het proces van het vinden en ordenen van spraakklanken en het plannen van de bewegingen voor de spraak kon ik identificeren. Dit was niet het geval in de herhaaltaak, dus deze taak werd uit het protocol gehaald.

In *Hoofdstuk 3* werd het protocol getest in oudere volwassenen. Ook in deze groep deelnemers konden alle vier processen van het spreken geïdentificeerd worden. Ik onderzocht of de processen met voortschrijdende leeftijd veranderen. De oudere volwassenen hadden in elke taak meer tijd nodig om te antwoorden, maar de processen van het spreken waren niet vertraagd in de EEG data. Misschien controleerden de oudere deelnemers hun antwoord nog voordat ze antwoordden. Het tijdsvenster en het patroon van de processen in de EEG data verschilden tussen de jongere en de oudere volwassenen, dus de processen leken met voortschrijdende leeftijd minder efficiënt te worden. In de jongere en oudere volwassenen werden de effecten die aan de processen gerelateerd zijn met dezelfde electroden gemeten, dus de neuronen die bij de processen betrokken zijn leken niet te veranderen met voortschrijdende leeftijd.

In *Hoofdstuk 4* werden eerst de processen in beide groepen personen met afasie onderzocht. Manipulaties van gestoorde processen konden niet in de EEG data geïdentificeerd worden. Zo kan ik de groepen niet onderscheiden, omdat de afwezigheid van een kenmerk door verschillen in de ernst van de stoornis in de groep kan komen. Daarna werden de processen vergeleken tussen de personen met afasie en met hen gematchte neurologisch gezonde personen. Zoals verwacht verschilden personen met afasie en spraakapraxie van de neurologisch gezonde personen in het plannen van bewegingen voor de spraak, maar personen met afasie en een stoornis in fonologisch coderen verschilden ook in dit proces van de neurologisch gezonde deelnemers. De personen met afasie en een stoornis in fonologisch coderen waren waarschijnlijk nog bezig met het fonologisch coderen van de tweede lettergreep, terwijl ze de bewegingen voor de spraak van de eerste lettergreep aan het plannen waren. Dus, zo kan ik de groepen personen met afasie niet van elkaar te onderscheiden. De vergelijking van het verschil in de EEG data tussen personen met afasie en een stoornis in fonologisch coderen en gematchte neurologisch gezonde personen en het verschil in de EEG data tussen personen met afasie en spraakapraxie en gematchte neurologisch gezonde personen liet alleen in het proces van het plannen van de bewegingen voor de spraak een verschil zien. Dus, het protocol kan gebruikt worden om een stoornis in fonologisch coderen en spraakapraxie van elkaar te onderscheiden in personen met afasie.

Een algemene discussie over de bevindingen uit Hoofdstukken 2, 3 en 4 werd beschreven in *Hoofdstuk 5*. Ook werden er aanbevelingen gedaan voor toekomstig onderzoek. Als het protocol op individueel niveau ingezet kan worden, dan kan de logopedist therapie op maat geven. Ook zou er onderzocht kunnen worden of er met het protocol met EEG vooruitgang in bepaalde processen gemeten kan worden in personen met afasie en spraakapraxie.

About the author

Jakolien den Hollander was born on April 30st 1989 in Zwolle, the Netherlands. In 2010, she obtained a Bachelor of Arts in Linguistics from the University of Groningen. She graduated from the Erasmus Mundus program in Clinical Linguistics (EMCL) in 2012 with a Master of Science from the University of Potsdam in Germany, the University of Groningen and the University of Eastern Finland in Joensuu. Thereafter, she contributed to a research project on communication in children with multiple disabilities at the University of Groningen as well as to a research project on dysarthric speech in Parkinson's Disease at INCAS^3 in Assen, the Netherlands. In 2015, she commenced the International Doctorate for Experimental Approaches to Language And Brain (IDEALAB), for which she was awarded with an Erasmus Mundus Joint Doctorate Fellowship. Her PhD project with the title 'Differentiating a phonological encoding disorder from Apraxia of Speech in individuals with aphasia by using EEG' was supervised by Prof. dr. Roelien Bastiaanse, dr. Roel Jonkers and Prof. dr. Lyndsey Nickels. Jakolien is married to Arne Blankerts since 2016. In 2019, their daughter Keira was born. At the time of printing this dissertation, Jakolien is participating in a Data Science Bootcamp at neuefische in Hamburg, Germany, and plans to start her career as a data scientist.

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