Electrophysiological correlates of phonological and temporal regularities in speech processing

The brain makes use of regularities in the sensory environment to formulate predictions that facilitate perception. Such predictive capacities have been proposed to influence neural processing across multiple domains, including speech and language processing. This dissertation aimed to investigate the electrophysiological correlates of phonological and temporal regularities in speech processing. In three empirical studies, we investigated the neural sensitivity to variations in phonotactic probability (phonological regularity) and syllable stress patterns (temporal regularity) in native Dutch speakers. We first developed a passive oddball paradigm where we manipulated these features simultaneously in typically reading adults (Chapter 2). This paradigm was then applied to dyslexic readers, to investigate how they differ in their sensitivity to these features (Chapter 3). Here, we also investigated how the time-frequency correlates of the mismatch response differ between variations in phonotactic probability and syllable stress. Finally, we made a step towards speech production, where we tested the sensitivity of the N1 and P2 ERP components to phonological and temporal regularities in self- and externally triggered speech (Chapter 4). The following section contains a summary and discussion of the findings presented in this dissertation.

1 Summary

Current theories of neural processing propose that the brain formulates predictions of upcoming sensory events to facilitate perception (Engel et al., 2001; Raichle, 2010; Rao & Ballard, 1999). Such predictions are based on learned regularities in the environment, and can be formed about both the content and the timing of external sensory input (Arnal & Giraud, 2012), as well as the sensory consequences of our own actions (Wolpert & Miall, 1996). These principles also apply to speech processing. The speech signal is highly complex and variable, and yet listeners are able to understand speech even when sensory input is suboptimal (e.g., Hannemann et al., 2007). Predictive processing has been proposed as a mechanism to facilitate this seemingly effortless processing at multiple levels of linguistic analysis (e.g., DeLong et al., 2005; Freunberger & Roehm, 2016). Even in the absence of semantic or lexical content, our brain is tuned to regularities in the speech signal (Bonte et al., 2005; Emmendorfer et al., 2020; Vidal et al., 2019). In any given language, certain combinations of speech sounds or stress patterns are more likely to occur than others, and sensitivity to such sublexical regularities can guide perception and facilitate production (Edwards et al., 2004; Luce & Large, 2001; Munson, 2001; Vitevitch et al., 1997; Vitevitch & Luce, 2005). In three empirical chapters, this dissertation investigated predictive processing of two of these types of regularities, phonotactic probability and syllable stress, using EEG.

In Chapter 2, we set out to investigate the neural sensitivity to variations in phonotactic probability and syllable stress using the identity mismatch negativity (Eulitz & Lahiri, 2004) in a passive oddball paradigm. Prior research in native Dutch speakers has shown that the MMN is modulated by variations in phonotactic probability in both children (Bonte et al., 2007) and adults (Bonte et al., 2005; Noordenbos et al., 2013). In these studies, deviants with high phonotactic probability elicited a larger MMN compared to deviants with low phonotactic probability, indicative of facilitated perceptual change detection for high probability items. MMN sensitivity to syllable stress variations has been demonstrated in fixed-stress languages such as Finnish (Ylinen et al., 2009) or Hungarian (Honbolygó et al., 2004; Honbolygó & Csépe, 2013; Ragó et al., 2014), however studies in languages with variable stress patterns such as Dutch are sparse and often focus on the MMN sensitivity to acoustic markers of stress rather than more abstract sensitivity to variations in stress patterns (e.g., Tong et al., 2014; Zora et al., 2015). The current approach aimed to, for the first time, investigate MMN sensitivity to phonotactic probability and syllable stress patterns when they are manipulated simultaneously, as these features also vary simultaneously in natural speech. Our findings support previous observations of MMN sensitivity to variations in phonotactic probability (Bonte et al., 2005; Noordenbos et al., 2013), with high phonotactic probability deviants eliciting an earlier MMN compared to low phonotactic probability deviants. No modulation of the MMN by variations in syllable stress was found, suggesting that Dutch speakers may not be sensitive to this feature when it is manipulated in pseudowords. While we did not observe any direct interactions between phonotactic probability and syllable stress, the current modulation pattern (latency effect) differed from prior observations with similar stimuli (amplitude effect; Bonte et al., 2005). A possible explanation for this discrepancy might be that the simultaneous manipulation of syllable stress changes the processes underlying the amplitude effect observed in previous studies.

In Chapter 3, the oddball paradigm first implemented in Chapter 2 was applied to dyslexic readers. Here, we aimed to investigate whether individuals with dyslexia show altered sensitivity to phonotactic probability and syllable stress. Reduced sensitivity to variations in phonotactic probability has been observed in both children (Bonte et al., 2007) and adults (Noordenbos et al., 2013) with dyslexia. Further evidence suggests that children who later develop reading impairments show atypical MMN responses to variations in syllable stress (Schaadt & Männel, 2019), in line with frameworks suggesting that impaired encoding of speech rhythm may be an underlying factor in developmental dyslexia (Goswami, 2011; Ladányi, Persici et al., 2020; Lallier et al., 2017). Here we aimed to replicate previous findings on phonotactic probability in an adapted paradigm where it was manipulated simultaneously in syllable stress, and for the first time investigated the sensitivity of Dutch adults with dyslexia to variations in syllable stress. Additionally, using time-frequency analysis, we investigate the oscillatory correlates of phonological and temporal change detection. Both formal and temporal deviants elicit a significant MMN, indicating auditory change detection. Our MMN findings support previous observations of reduced sensitivity to phonotactic probability in dyslexic adults (Noordenbos et al., 2013). We did not observe any MMN modulation of syllable stress in dyslexics or controls. The distinct oscillatory correlates of the mismatch negativity for processing formal and temporal deviants are a particularly interesting finding in this chapter. Deviants differing from the standard in phonotactic probability (formal deviants) exhibit the typical increased theta ITC associated with sensory memory processes underlying deviancy detection (Fuentemilla et al., 2008; Hsiao et al., 2009), which was enhanced in dyslexic readers, in line with previous observations (Halliday et al., 2014). This enhanced phase-locking to deviant stimuli in dyslexic readers may reflect an involuntary attention switch to evaluate the deviant stimulus (Fitzgerald & Todd, 2020; Tamura et al., 2015), suggesting atypical auditory interference control (Gabay et al., 2020). Deviants differing in syllable stress (temporal deviants) on the other hand showed a decrease in delta/theta ITC and did not differ between dyslexic and typical readers. This response pattern likely suggests a disruption in phase-locking to the temporal deviant relative to the standard, due to the change in the temporal structure of the stimulus when the syllable stress pattern is altered. Taken together, these time-frequency results suggest dissociable oscillatory mechanisms underlying the mismatch response for formal and temporal deviants. We observed atypical processing of formal deviants in dyslexics, in line with prior reports (Bonte et al., 2007; Halliday et al., 2014; Noordenbos et al., 2013), however, no differences between dyslexic and typical readers in processing temporal deviants. Some reports have highlighted that the difficulties associated with stress perception may rather be related to explicit stress awareness, or task demands when stress perception is tested with an explicit task (Anastasiou & Protopapas, 2015; Barry et al., 2012; Mundy & Carroll, 2012, 2013). Thus, dyslexic readers may not differ from controls when this sensitivity is tested implicitly as in the passive oddball paradigm.

In Chapter 4, we aimed to test whether predictability of phonotactic and stress regularities are exploited differently in speech perception and production. For this, we applied a motor-to-auditory paradigm, where participants listen to stimuli that were either self-triggered via button press, or externally generated. In such a paradigm, self-triggered stimuli lead to a suppressed neural response compared to identical stimuli that are externally presented, where the magnitude of this suppression, termed motor-induced suppression (MIS), depends on the predictability of the stimuli (e.g., Bäss et al., 2008; Knolle et al., 2013a). While such paradigms have been applied using tones (Knolle et al., 2013a), vowels (Knolle et al., 2019), and single syllables (Ott & Jäncke, 2013), the current approach was the first to use more complex bisyllabic pseudowords varying in phonotactic probability and syllable stress. We observed an interaction between phonotactic probability (high vs. low) and condition (self- vs. externally triggered) on N1 amplitude, however no post-hoc t-tests were significant. P2 amplitude was modulated by syllable stress, with first syllable stress items eliciting a larger P2 compared to second syllable stress items, likely reflecting acoustic differences between the stimuli. These findings provide preliminary evidence suggesting that phonotactic regularities influence processing of self- and externally produced speech differently, which should be followed up on in future investigations.

Taken together, the results presented in this thesis suggest that Dutch-speaking adults are sensitive to variations in phonotactic probability, indicated by variations in MMN latency (Chapter 2). This sensitivity is reduced in adult dyslexic readers (Chapter 3), suggesting that sensitivity to phonotactic regularities may play an important role in successful reading development. While Dutch adults, with and without dyslexia, are able to perceptually distinguish between different stress patterns (Chapters 2, 3 and 4), we did not observe facilitated processing of more typical stress patterns, suggesting that it may not be a particularly relevant cue in sublexical speech processing of single pseudowords in a language with variable stress patterns. Together with the time-frequency results (Chapter 3), these findings suggest that phonotactic probability may be a more important cue for speech processing of individual pseudowords, and that the phonological and temporal regularities are processed independently at the sublexical level.