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Network-state dependent effects in naming and learning

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Network-state dependent effects in naming and learning.

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Abstract

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation device that offers promise of more effective and longer lasting rehabilitation effects and a tool that can be used to causally manipulate brain function. One area that has reaped particular benefit is in the study of language processing in adults with and without brain damage. In the face of inconsistent findings, and the dawning realisation that tDCS is not as easy to use as first thought, more attention to the basic questions of how and when tDCS can affect language processing is needed. The general aim of this thesis was to better understand how changing states within the language network affected the response to tDCS in healthy adults. This thesis extends previous reported effects of tDCS on confrontation naming and word learning, by examining the impact of participant, task, and stimulus-level characteristics on expected tDCS effects in healthy adults. The main findings were: 1) tDCS did not facilitate response times during confrontation naming, irrespective of the activation state of specific stimuli, or region of interest targeted 2) bilingual experience facilitates word learning but phonological memory abilities and language switching abilities cannot explain this effect, highlighting the potential impact of experiential and cognitive factors on task performance and 3) the effects of stimulation on word learning are likely to be much weaker than previously reported, at least in single sessions, and may interact with participant, task and stimulus-level characteristics in a complex manner. It is too early to abandon tDCS as a neuroscience tool but careful consideration of experiential, cognitive, and biological factors that may interact with task performance need to feature more heavily in the design and execution of future studies. Code and data for each of the chapters where this is relevant can be accessed via the Open Science Framework site for this thesis (OSF site: http://bit.ly/JPayne_PhD_OSF).

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Author Declaration

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy.

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

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Thesis Overview

The application of tDCS to the study of cognition has grown exponentially since the reintroduction of the technique at the turn of the century (M. A. Nitsche & Paulus, 2000). Despite the low spatial and temporal resolution, tDCS has been reported to produce modulation of specific cognitive and neuronal functions (Hartwigsen, 2015; Harty et al., 2016). Recently, attention has turned the role of network-level activation states and their interactions with tDCS to explain these specific effects (Fertonani & Miniussi, 2017; Miniussi et al., 2013). In studies of language processing, network-state dependent interactions have not been explicitly investigated. The overall goal of this thesis was to investigate the role of network-activity states within the language network and subsequent interactions with tDCS, from a multi-level perspective. Multi-level refers to the influence of participant, task, and stimulus-level factors that could modify tDCS effects on behavioural language processing performance.

The first introductory chapter provides an overview of the major components of lexical processing in the healthy adult brain, as well as an overview of language learning and factors that facilitate this process. A second introductory chapter covers the general application of tDCS, the proposed mechanisms of action, and the primary impact of this technique on naming and word learning performance.

The study reported in chapter 3 investigated site and timing-dependent effects of tDCS on the evolution of repetition priming in picture naming tasks, in healthy younger adults. Two groups of healthy adults received stimulation to either left inferior frontal or posterior superior temporal regions, whilst undergoing active and sham tDCS. Online and offline effects of tDCS on naming response times were compared over three sets of items, each with differing levels of within-session naming experience. The aim of this manipulation was to better understand how tDCS applied at different sites within the language network and

subsequently how stimulation effects were affected by changing levels of activation at the item-level, examined during and shortly following application of tDCS.

In chapter 4, a rationale for studying the effect of tDCS on foreign language vocabulary learning is presented along with detailed overview of the stimulus development processes critical to the experiments presented in Chapters 6 and 7. Chapter 5 provides an overview of a brief name agreement study to validate name agreement with a sample similar to the intended sample for the latter experimental chapters.

Chapter 6 provides a test of the associative learning task adapted in Chapter 4, to understand the behavioural effects that arise in monolinguals and bilinguals. This study investigated the bilingual word learning advantage in two groups of healthy adults: a monolingual English group and a Welsh-English bilingual group. Several reports have demonstrated superior performance of bilingual participants in explicit foreign vocabulary learning tasks which may be related to 1) superior phonological working memory abilities, 2) may be moderated by the degree of switching behaviour, or 3) a general advantage in learning new vocabulary because of experience of using two languages. The paradigm showed sensitivity in detecting large and subtler effects on learning as a function of stimulus and participant-level factors. These insights demonstrated that value of such a task in detecting potential facilitation effects of tDCS.

In Chapter 7 the effect of active tDCS on real foreign language learning was investigated. Active and sham tDCS was applied to left posterior superior temporal regions, in a group of monolingual English speakers, during an associative word learning task. Offline effects of tDCS on backward translation immediately, the day after, and at one-week follow-up and explored potential moderating effects of phonological working memory on learning and the effects of tDCS.

The final chapter comprises a discussion of the main contributions of this thesis. Implications of findings in the context of the current literature are discussed and suggestions are made regarding the approach to future exploration of tDCS effects on language processing.

Running head: LANGUAGE, LEARNING & MEMORY

Chapter 1: Language, Learning and Memory

Humans have a remarkable ability to learn and store words. In infants there is an explosion in comprehension and production of words in the second year of life (Mayor & Plunkett, 2010; McMurray, 2007). By the age of 20, an average adult is thought to know around 42,000 words (Brysbaert, Stevens, Mander & Keuleers, 2016). Word knowledge continues to increase with advancing age, and is further augmented through education and multilingual experience (Keuleers, Stevens, Mandera & Brysbaert, 2015). The ability to use and learn languages is foundational to human cognition and the human experience. As such, understanding the cognitive and neurobiological underpinnings of language abilities has been a corner stone of psychological science over the last century. This chapter provides an overview of the cognitive mechanisms implicated in lexical processing, the neurobiological network that underpins language production and comprehension, as well as discussion of the processes that underpin acquisition of new words as adults.

1.0 Central Aspects of Lexical Processing

In the simplest sense, a lexical representation is the resulting output formed from the connection between the semantic representation of a concept and its label or lexical entry. The existence of conceptual and lexical levels of representations are uncontroversial. The conceptual level is a store of features and attributes that when combined form an abstract representation of an object or a concept. For example, the conceptual representation of a dog could be made up in part through combination of the following features: four-legged, mammal, barks, has fur, wags tail, dislikes cats. The lexical level contains representations of the labels associated with specific concepts as wordforms. The lexicon is commonly referred to as a mental dictionary and reflects long-term memory storage of the phonological form of words encountered over a lifetime. In production, lexical access proceeds through two steps (Dell, Nozari & Oppenheim, 2014; Dell & Reich, 1981; Garrett, 1975; Levelt, 1989; Rapp & Goldrick, 2000). The first involves the mapping of an abstract concept to a lexical unit. The

second involves mapping of an abstract lexical unit to its phonological representation. In comprehension, the stages in lexical access are reversed. Analysis of an incoming speech stream must be converted into phonetic units and matched against stored representations of known words. The word form can then be used to draw down information from the conceptual level to provide meaning for the utterance. Precisely, how these steps proceed has been the focus of empirical and computational work for the last three decades (production: Dell et al., 2014; comprehension: Weber & Scharenborg, 2012). The next section outlines the general principles of lexical selection.

1.1 Principles of Lexical Selection

1.1.1 Spreading Activation

There is a general consensus that activation spreads between nodes within the conceptual and lexical levels. For example, activation at the conceptual levels spreads to other semantically related concepts which has distinct consequences for comprehension and production. Semantically related primes facilitate word recognition (e.g., Swinney et al., 1979), whereas word production is slowed on presentation of semantically related objects (e.g., Lupker, 1979). Considerably more debate concerns the nature of activation flow between levels. Early views, that processing proceeds in a modular fashion (Levelt, Roelofs & Meyer, 1999; Roelofs, 1992, Roelofs, 1997), have largely been abandoned in view of the considerable evidence that supports cascaded processing between levels (Dell et al., 2014 for review). Cascaded activation is characterised by the spreading of activation from the conceptual level to the lexical level before processing has completed at the earlier stage. In production, most researchers utilise naming tasks, as they provide a simpler approximation of the stages in speech production: access to meaning, access to lexical representation, and access to phonological form for articulation. Ferreira and Griffin (2003) provided strong evidence for cascaded activation in naming tasks. Ferreira and Griffin (2003) examined error

responses during picture naming following the presentation of cloze sentences that primed a word semantically related to the target picture, a homophone of the target picture name, or an unrelated word. Both semantic and homophonic probes resulted in substitutions of the correct object names more frequently than unrelated probes, suggesting that both semantic and phonological information impact on lexical selection.

Further evidence of cascaded activation comes from speakers of multiple languages. In their classic study, Costa, Caramazza and Sebastian-Galles (2000) demonstrated strong evidence for a universal principle of cascaded activation between semantic and lexical levels. Catalan-Spanish bilinguals named pictures that were either cognates or noncognates in the two languages. Cognates share phonological and semantic information between languages. Thus, if lexical selection proceeds in a cascaded fashion, retrieval of cognate object names should be facilitated relative to non cognates. This is exactly what Costa et al. showed. The cognate facilitation effect was observed in both L1 and L2 naming contexts but was not present in monolingual Spanish speakers, for whom the phonological similarity of cognates has no bearing on lexical access. The now classic effect has also been observed numerous times in written (Dijkstra et al., 1998) and spoken word recognition studies (Carroll, 1992; van Heuven & Dijkstra, 2010) and highlights the universality of spreading activation as a key principle of lexical access proceeding from meaning-to-phonology in production, and vice versa in comprehension. In bilinguals, spreading activation includes lexical representations in both languages and this finding is underpinned by evidence like the cognate facilitation effect that demonstrates influence from a second language even when it is not the target language for a given task (Kroll, Bobb, & Wodniecka, 2006; Martin, Dering, Thomas, & Thierry, 2009; Spalek, Hoshino, Wu, Damian, & Thierry, 2014). Although most models of lexical access have built on the basis of monolingual language processing, the general principles that underpin lexical access appear to be common to multilinguals.

1.1.2 Lexical Selection is Competitive

1.1.2.1 Production

Many models of lexical access in production assume that the process of conceptual-to-lexical activation is competitive (Dell et al., 2014). Computational accounts of lexical retrieval assume that selection of a given concept is achieved through a winner takes all approach; that the concept with greatest cumulative activation is selected as the target for use. At the conceptual level, spreading activation to semantically related nodes result in increasing activation for both target and related nodes, leading to competition for selection. This idea is thought to explain the semantic interference effect classically observed in speech production tasks. Semantic interference is characterised by the progressive slowing of response times to object pictures that are preceded by other semantically related objects (Damian et al., 2001; Howard et al., 2006), although recent findings have called the competitive selection account of speech production into doubt (Mahon et al., 2007; Oppenheim et al., 2010)

1.1.2.2 Comprehension

In models of speech comprehension, competitive selection is a foundational feature of the speech recognition element of most models (Weber & Scharenborg, 2012). In most models, word recognition is achieved through activation of phonetic features from incoming auditory signals, which results in parallel activation of phonologically related words, leading to a competitive selection mechanism between candidate word forms, where the stored representation that best matches the input wins out. However, the nature of the information flow from word form representations to concepts is a contentious issue in models of speech recognition. Many models have simply not been implemented to address the flow of information between levels (Weber & Scharenborg, 2012). The Distributed Cohort Model (DCM, Gaskell & Marslen-Wilson, 1997) explicitly attempts to address this gap. The DCM assumes that activation of form and meaning information happens in parallel and that

semantic information arises through competitive activation of semantic features, activated by incoming phonological information from multiple activated lexical candidates. The process of access to lexical semantic information is thus a continuous process that adapts dynamically to the incoming speech stream. The competitive aspect of this account at least may be considered complementary to the competitive lexical access described in cascaded interactive models of speech production.

1.2 Lexical Access as a Dynamic System

Models of lexical access in production and comprehension have assumed static states in activation weights for conceptual and lexical nodes. A recent proposal for production has implemented lexical selection as an incremental learning mechanism that does not rely on competition for selection (Oppenheim et al., 2010). There is considerable evidence that the lexical system is adaptive. Repetition of pictures or words results in dramatic short-term changes in accessibility, with effects continuing for weeks and months (Francis, 2014). Lexical frequency, familiarity, and age of acquisition effects provide evidence that repeated exposure implicitly strengthens the representation of known words and are thus easier to retrieve (Alario et al., 2004). In the Dark Side model, Oppenheim et al. (2010) implement the dynamic nature of the lexical system through two parallel processes. On encountering a target picture, the strength of the connection weights between conceptual nodes and lexical representations are strengthened. At the same time, connection weights for non-target, competing mappings are reduced, resulting in some unlearning for those less relevant connections. During lexical retrieval these weights receive a continuous boost to their activation state until activation of a lexical candidate is sufficiently high and is selected for production. This model presents lexical retrieval not as an all or one access problem but a continual learning process that can effectively capture phenomena such as frequency effects, repetition priming, and because of the sensitivity to competitor activation, semantic

interference effects. It is also supports that idea of continual integration of strengthening of representations for known words over short and long term intervals.

The incremental learning components embodied in the Dark Side model (Oppenheim et al., 2010) reflect a dynamic systems perspective on language processing and cognition in general (Bot, 2008; Bot et al., 2007; Elman, 1995). Elman (1995) argued that static models reflect a modular view that does not reflect how the brain actually works. Instead, he argues for a developmental perspective, where networks self-organise and re-organise in relation to the nature of their input, through interaction with the environment. Dynamic systems are self-organising and the output from such systems is dependent on the starting state. These systems are fully interconnected such that a change in one specific variable will influence all other variables in some way, which gives rise to individual differences in learning and processing of language more generally (De Bot, 2008). This perspective as language processing as a dynamic rather than static process is rapidly gaining ground.

One approach to understanding how language develops and is processed uses a learning algorithm called a self-organising map (SOM; e.g., Kohonen, 2013). Computational models built using the SOM algorithm principles embody a dynamic systems approach and can accurately capture typical and disordered linguistic and cognitive behaviours reported in children and adults. A SOM utilises an unsupervised learning algorithm that builds connections through co-occurrence of features over several thousand epochs that are mapped onto a 2D visual representation. One of the features of these maps is that similarity between input (e.g., concepts from the same category, phonological neighbours) can be readily observed in a manner concurrent with natural language processing. Although single SOMs have been useful for understanding processing within levels, most models make use of multiple SOM that represent each level of language processing separately (i.e., semantic, phonological, orthographic). Each single SOM is connected through associative links which

are strengthened through co-occurrence between input patterns and map representations at

multiple levels, using Hebbian learning principles (Hebb, 1949) that reflect the interactive,

cascaded nature of lexical processing in a manner that corresponds to long-term potentiation

effects at the neural level (Munakata & Pfaffly, 2004). These tools can be powerful in

demonstrating how language develops over time and can be manipulated to produce various

states in the network as a function of development or in response to additional variables, like

age of acquisition effects or simulations of early and late bilingualism (for an overview, Li &

Zhao, 2013). For example, the DISLEX model originally created by Miikkulainen (1993) as a

model of language processing in monolinguals can model patterns of behavioural

performance dyslexia and aphasia (Miikkulainen, 1997). DISLEX has been extended in a

recent series of studies to simulate the bilingual lexicon before being 'lesioned' to simulate

patterns of deficits in bilinguals with aphasia to aid in the prediction of rehabilitation success

(Grasemann, Sandberg, Kiran, & Miikkulainen, 2011; Kiran, Grasemann, Sandberg, &

Miikkulainen, 2013; Miikkulainen, 1993; Miikkulainen & Kiran, 2009). A recent

development in the literature comes from Shook and Marian (2013) who combined aspects of

the SOM approach with more tradition localist, connectionist models like the bilingual

interactive activation model (e.g., Dijkstra, Van Heuven, & Grainger, 1998) to simulate

speech comprehension effects in bilinguals. The Bilingual Language Interaction Network for

Comprehension of Speech (BLINCS; Shook & Marian, 2013) model produces maps that

show clear separation between the two trained languages of Spanish and English at all levels,

with borders between languages that reflect similarity between inputs form both languages.

On the semantic map, translation equivalents cluster together from both languages and

accurately capture the general assumption that semantic representations are shared between

languages in bilinguals (e.g., Francis, 2005). In the BLINCS model, orthographical-lexical

and phonological-lexical representations that are more similar within and between languages

lie closer in space than less similar representation on the map, reflecting lexical neighbourhoods and cross-linguistic similarity (i.e., cognates: tobacco-tabaco). These latter effects suggest that the assumption of distinct and separate lexicons in the bilinguals arises from natural separation of languages based on the features of the language, utilising the same principles as lexical organisation in monolinguals. The BLINCS model is able to accurately capture semantic priming and competition effects as well the effects of cross-linguistic influence, such as greater activation to cognates and translation equivalents over false cognates and non cognates (Blumenfeld & Marian, 2013; Costa et al., 2000, 2005; Dijkstra et al., 1999; Lemhöfer et al., 2004). Using similar principles as the BLINCS model (Shook & Marian, 2013), Zhao and Li (2013) were able to simulate patterns of cross-language priming performance based on the age of acquisition of an L2 using the DevLex-II model. In sum, SOM models present a neutrally plausible approach to modelling language acquisition and processing in monolinguals and bilinguals. Such models capture the dynamic nature of language processing, which has substantial implications for the study of language in general.

1.2 Neurobiological Basis of Language Processing

For most people, language function is served by a complex network of regions in both hemispheres of the brain but with a dominant role of the left-hemisphere (Carey & Johnstone, 2014; Corballis, 2012). The neuroanatomical and functional networks that underpin production and comprehension have been the topic of intense study since beginning of the last century. The rise of neuroimaging technologies like PET, fMRI and event-related potentials has accelerated our understanding over the last 30 years (Fedorenko & Thompson-Schill, 2014; Friederici, 2011; Indefrey, 2011; Price, 2012).

One recent approach that has gained ground over the last 15 years is the dual stream perspective on language processing (Hickok & Poeppel, 2007; Poeppel & Hickok, 2004; Saur et al., 2008). The dual stream model is inspired by ventral and dorsal stream models of visual

processing (Goodale & Milner, 1992; Milner & Goodale, 2008; Ungerleider & Mishkin,

1982). Incoming auditory signals are processed via primary auditory cortex bilaterally, and

phonological processing proceeds along bilateral superior temporal sulci. Middle-posterior

sections of the superior temporal sulcus appear to be specialised for phonological processing.

This region is sensitive to phonological neighbourhood density and has been proposed as the

site of the phonological lexicon (Graves et al., 2008; Okada & Hickok, 2006; Peramunage et

al., 2010; Prabhakaran et al., 2006). Additionally, this region appears to be activated more for

novel phonological to pseudowords relative to known words (e.g., Davis & Gaskell, 2009),

further indexing a role in access and storage of phonological sequences. Moreover, this

region also appears to support the maintenance of phonological representations, critical for

phonological working memory (Hickok et al., 2003; Leff et al., 2009; Costanza Papagno et

al., 1991; Vallar & Baddeley, 1984). From here, information processing is divided along two

pathways: a ventral form-to-meaning pathway, and a dorsal sound-to-articulation pathway.

The ventral pathway is weakly left-hemisphere dominant and is the route for mapping

phonological information to meaning specifically via bidirectional connections with posterior

middle and anterior inferior temporal sulci, making it critical for speech recognition. Sound-

to-meaning mapping appears to be accomplished via long-distance white matter connections

along branches of the inferior longitudinal fasciculus (ILF) that receives input from fusiform

gyrus, an area important for access to semantics (e.g., Wheatley, Weisberg, Beauchamp, &

Martin, 2005), and extends through the temporal lobe into the extreme capsule (Saur et al.,

2008). A number of studies have also highlighted the spread of activation from STS into

other cortical regions with increasing attention to meaning in speech recognition tasks (Price,

2012). The extent of the activation includes the middle and inferior temporal regions

discussed above, as well the fusiform gyrus, and hippocampus for access to long-term and

episodic representations of auditory word forms (Price, 2012). Additionally, activation

extends to regions of the parietal lobe including the left angular gyrus and this broader spread reflects the general consensus of a broad distribution of semantics throughout the brain (Hickok & Poeppel, 2007; Poeppel & Hickok, 2004). Additional support for a role of the ventral stream in sound-to-meaning mapping comes from studies that demonstrate associations between increased fractional anisotropy, functional and/or structural connectivity along these pathways and greater phoneme contrast and word learning success (Lopez-Barroso et al., 2011; F. C. K. Wong et al., 2011; P. C. M. Wong et al., 2007). Information from the sound-to-meaning pathways then interacts with ongoing activity in the inferior frontal gyrus (IFG). The posterior portion of IFG has been implicated in lexical selection and control of semantic competition and is functionally coupled with responses in posterior middle-temporal gyri (Krieger-Redwood & Jefferies, 2014; Moss et al., 2005; Wagner et al., 2001; Whitney et al., 2011).

Many of the processes involved in production overlap with comprehension. In particular, semantic activation during word retrieval during picture naming tasks occurs in left middle and posterior superior temporal regions with connected activation in left IFG (e.g., Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2011). However, articulation preparation and control is imperative to successful production and control of speech output. In the dual-route model, the dorsal pathway is thought to underpin sound-to-articulation processes and is implicated in motor-speech planning and rehearsal of speech, critical for speech perception and production. The dorsal pathway is strongly left lateralised. Acoustic information from the middle and posterior STS is processed by a region along the temporal-parietal junction dubbed area Spt (Sylvian parieto-temporal region; Hickok & Poeppel, 2007). Spt, under the dual stream model is thought to be involved in the integration of auditory and sensory motor information, critical for articulatory planning in the anterior insula, pre-motor, and inferior frontal gyri. This route from auditory input to articulation is

served primarily by two white matter tracts, the arcuate fasciculus (AF) and the superior longitudinal fasciculus (SLF). The AF and SLF connect the inferior parietal and temporal regions with frontal lobes. The SLF and dorsal portions of AF terminate in premotor cortex and with ventral, longer portions of the AF terminating in posterior inferior frontal gyrus (Catani et al., 2005; Catani & Ffytche, 2005; Saur et al., 2008).

1.2.1 Bilingual Language Processing

The models discussed above and the vast majority of neuroimaging studies of comprehension and production have been conducted in monolingual populations. There is general consensus that the same distributed network underpins language processing in monolinguals and multilinguals. A number of studies have demonstrate shared and overlapping representations for both languages (Indefrey, 2006; Perani & Abutalebi, 2005; van Heuven & Dijkstra, 2010). More generally, production or comprehension of the language acquired earlier in life results in lower levels of activation in relevant regions. Factors like language dominance and relative exposure lead to recruitment of some extra-linguistic resources (Hesling et al., 2012; Perani et al., 2003; Perani & Abutalebi, 2005; van Heuven & Dijkstra, 2010). In the case of cognates, activation patterns are indistinguishable between languages but production and comprehension of non cognates, particularly in the less proficient language show increased activation in posterior superior temporal regions, indicating more effortful retrieval (De Bleser et al., 2003). This relative distinction for less similar words in the two languages may reflect the 'distance' between lexical entries in an integrated lexicon as highlighted in computational models (Shook & Marian, 2013; Zhao & Li, 2013). Moreover, a considerable literature using event-related potentials has demonstrated robust evidence for non-selective access (Grossi, Savill, Thomas, & Thierry, 2012; Martin et al., 2009; Spalek et al., 2014; Wu, Cristino, Leek, & Thierry, 2013; Wu & Thierry, 2010, 2012). Non-selective access refers to the idea of activating representations form both

languages simultaneously whilst only consciously processing information in one of their known languages. Wu et al. (2013) demonstrated that non-selective access is an automatic process that occurs even when activation of lexical information is tangential to the task. In a visual search task, Chinese-English participants had to indicate whether they had seen a sequence of squares, circles or all words in four corners of a computer screen. On critical four-word trials, the translation of one of the words was phonologically or semantically related to Chinese translation for square or circle. Using eye-tracking, Wu et al. observed that Chinese-English bilinguals fixated for longer on critical words than on control trials where there was no relationship between any of the words. This pattern was no observed in a group of monolingual controls.

One domain that has received considerable attention is cognitive control. Day-to-day management of interference and co-activation of multiple languages is thought to draw on cognitive control resources more so than in monolingual language processing (Bialystok et al., 2012). Several studies have examined the role of cognitive control during language production in bilinguals and have highlighted a distributed network of cortical and subcortical regions that serve the additional demands of managing two languages (Abutalebi & Green, 2007; Green & Abutalebi, 2013; Hervais-Adelman et al., 2011; Luk et al., 2012). These demands may alter the functional connectivity or the recruitment of specific regions during language processing (Abutalebi et al., 2009), which may have implications for tasks such as novel word learning or control of lexical interference relative to monolinguals (Bartolotti, Marian, Schroeder, & Shook, 2011; Bartolotti & Marian, 2012; Blumenfeld & Marian, 2013; Kaushanskaya & Marian, 2009a; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016).

1.3 Interaction of Lexical Processing and Memory

Lexical retrieval is an exercise in long-term and episodic memory retrieval and learning, particularly in the case of perception (Goldinger, 2007). There is considerable evidence that speech processing leads to specific episodic traces that contain details about the specific event and encode characteristics of specific speakers. Evidence for such an effect comes from studies that demonstrate stronger repetition priming effects for utterances from the same versus different speakers (Church & Schacter, 1994; Goldinger, 1996; Schweinberger et al., 1997) and observations of rapid perceptual learning in response to individual vocal features (Alain et al., 2007; Hawkey et al., 2004). However, engaging in conversation involves bringing to bear pre-existing representations of speech sounds stored in long-term memory. Clearly, integrating new perceptual information with older established representations is a challenge and yet new information does not catastrophically interfere with the old.

One influential proposal that attempts to explain the integration of newer, rich episodic information with longer-term, established representations, comes in the form of the complimentary learning systems (CLS) approach to memory (McClelland et al., 1995). The CLS account propose two independent but interconnected memory systems: a faster hippocampal and medial temporal lobe system that rapidly encodes new episodic memories and a slower cortical memory system that consolidates new information with old in an interleaved manner over much longer periods of time. The slower system has evolved to develop abstract, general knowledge about the world based on statistical co-occurrences, in contrast to the specific, stimulus driven memories held in the faster hippocampal system (Goldinger, 2007; McClelland et al., 1995). The hippocampus receives input from multiple cortical systems and integrates this information to form associations between incoming information streams, creating a mechanism of cyclical learning between the two systems.

Increasing exposure will strengthen the episodic trace and subsequently the longer-term representation of those associations. These in turn help to explain rapid effects of stimulus-dependent repetition priming in the immediate and longer term.

1.4 Complementary Learning Systems Account of Word Learning

Davis and Gaskell (2009; Ullman & Lovelett, 2018) took the CLS proposal and integrated it with knowledge of speech perception mechanisms outline in the Distributed Cohort Model (DCM; Gaskell & Marslen-Wilson, 1997) specifically, to provide a framework for understanding novel word learning in adults. Novel word learning involves three basic processes. First, incoming speech needs to be processed and representation of that form needs to be created. Second, access to the meaning of the word is required. Third, associative connections need to be rapidly made between form and meaning. These initial processes rely on basic speech comprehension mechanisms highlighted in earlier sections. Initial associative links between form and meaning are created as episodic memories in the hippocampus, a process called fast mapping (Coutanche & Thompson-Schill, 2014), and strengthened through repeated exposure. Over a period of consolidation, or through distributed episodes of practice, novel lexical forms are gradually integrated into the participants existing lexicon, as indexed by engagement of novel forms in lexical competition (Breitenstein et al., 2005, 2007; Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, et al., 2009; Dumay & Gaskell, 2005, 2007; Gaskell & Dumay, 2003; Lindsay & Gaskell, 2013, 2009; Tamminen et al., 2012; Tamminen & Gaskell, 2008, 2013; Tham et al., 2015). This framework provides a ready explanation for integration of novel forms into the existing lexicon that is neutrally efficient and draws on existing input and output mechanisms, as well as general principles of memory processing.

1.5 Factors that Facilitate Word Learning

When considering how word learning is accomplished a number of potential factors have to be considered. Potential moderators of learning success appear at the level of

individual differences between participants, as a function of the characteristics of the

language and nature of specific word forms to be learned, and a number of external factors.

1.5.1 Participant Factors

1.5.1.1 Motivation and Aptitude

There is considerable variability between individuals in their ability to learn new

words. Factors like a participant's motivation and attitude towards learning a new language

(e.g., Masgoret & Gardner, 2003; see also Ripolles et al., 2014 for fMRI evidence of the role

of reward in word learning), as well as participants' general aptitude have been the focus of

second language acquisition research for many decades (Li, 2014; Robinson, 2005).

Generally, aptitude is considered to be a range of cognitive abilities drawn on during

language acquisition and performance, that interacts with environmental factors that

influence the learning context (Robinson, 2005). Although aligned with cognitive

psychological approaches to understanding individual differences in learning success, the

specific nature of the 'cognitive abilities' that underpin aptitude is vague. Moreover, Li

(2014) reported generally weak predictive value of general aptitude measures and noted the

heterogeneity in use and make-up of general aptitude tests. As a general basis for

understanding word learning success, the role of general aptitude may be better evaluated

through examination of specific cognitive functions.

1.5.1.2 Phonological Working Memory

One key determinant of novel word learning success is an individual's phonological

working memory ability. Phonological working memory underpins an individual's ability to

maintain spoken sequences in working memory (Gathercole & Baddeley, 2014).

Phonological working memory is classically assessed through immediate serial recall of short

sequences of words. Immediate serial recall performance is positively correlated with

performance on nonword repetition and digit span tasks (Gupta, 2003). Performance on such tasks is positively correlated with total vocabulary size in children (Gathercole et al., 1999; Gathercole & Baddeley, 1989) and with learning success. and retention of novel words in healthy and brain-damaged individuals (Atkins & Baddeley, 1998; Gupta & Tisdale, 2009a, 2009b; Leff et al., 2009; Vallar & Baddeley, 1984). Gupta and Tisdale (2009) have demonstrated that phonological working memory ability may causally underpin nonword repetition performance and subsequent gains in vocabulary size, as well as word learning ability. Amongst adults, the role of phonological working memory ability in novel word learning ability is a robust finding and likely a key determinant of an individual's aptitude in this domain.

1.5.1.3 Linguistic Experience

There is now ample evidence to support the intuitive notion that speakers of multiple languages are more adept at learning a new language than speakers of only one language (Bartolotti et al., 2011; Bartolotti & Marian, 2012; Bradley, King, & Hernandez, 2013; Kaushanskaya & Rechtzigel, 2012; Margarita Kaushanskaya, 2012; Kaushanskaya & Marian, 2009a, 2009b; Papagno & Vallar, 1995; van Hell & Mahn, 1997). Papagno and Vallar (1995) were the first to document this effect experimentally. Italian multilingual and monolingual participants took part in two paired associative learning tasks – one included Italian words and the other Russian words. Performance between monolingual and multilingual participants was similar for Italian paired associate learning but multilinguals outperformed monolinguals in learning Russian. In addition, the multilinguals in this study showed better performance on tasks tapping phonological working memory abilities, which Papagno and Vallar interpreted as the underlying explanation for the bilingual advantage that they observed. However, more recent evidence suggests that greater phonological working memory capacity is not generally observed amongst multilinguals (Ratiu & Atkins, 2015; cf. Kroll, Michael, Tokowicz &

Dufour, 2002). Therefore, phonological working memory capacity may be fundamental for word learning in general but it is unlikely to explain the bilingual advantage in word learning (Kaushanskaya, 2012).

The bilingual word learning advantage may also be explained by other variables. Kaushanskaya and Marian (2007) presented evidence that the bilingual word learning advantage might only manifest itself for simultaneous or early bilinguals over monolinguals, but there is little research in this area. One key variable of interest is cognitive control. Multilinguals must manage and control the use of multiple languages on a day to day basis and this is thought to give rise to a general advantage in inhibitory control over monolinguals (Bialystok et al., 2012). A number of studies have demonstrated that bilinguals are better able to manage interference from competitors during retrieval of novel vocabulary compared to monolinguals (Bartolotti & Marian, 2012) although inhibitory control abilities may be maximally useful when language interference is high (Bartolotti et al., 2011). However, considerable debate surrounds the existence of a general cognitive control advantage for bilinguals. Hilchey and Klein (2011) failed to demonstrate a consistent bilingual advantage in executive control in their meta-analysis and highlight the narrow, and very specific, nature of the bilingual populations under study in these cases. One recent claim suggests that proficiency in two languages may not be enough to result in cognitive control advantage but rather that specific characteristics may give rise to a cognitive control advantage (Luk et al., 2011). One proposal is that the degree of switching between languages may in fact facilitate cognitive control (Emmorey et al., 2008; Prior & Gollan, 2011; Verreyt et al., 2016), and by that view may also moderate the word learning advantage if cognitive control abilities underpin the ability to control interference between competing novel and known word forms (Kaushanskaya & Marian, 2009a).

1.5.2 Language and Word-Level Similarity

Actual and perceived similarity between two languages or word forms in those languages can facilitate processing. The key contributors are typological distance, at the language level, and aspects of form similarity, at the word level.

1.5.2.1 Typological Distance

Typological distance refers to historical and/or perceived similarity between two languages. Most learners have little appreciation of the historical changes and development of the language they intend to learn. Nor does it have any real bearing on their ability to learn new words in an unknown language (Carroll, 1992, p. 102; Kellerman, 1983). Kellerman (1983) introduced the idea of psychotypology: what matters for learning is an individual's *perception* of the similarities between language rather than any meta-linguistic knowledge about the etymology of words in two languages. Psychotypology is an important factor when encountering novel forms from an unfamiliar language. Words from a less similar language are more difficult to learn than languages more closely related to one another (Papagno & Vallar, 1995; Schepens, van der Slik, & van Hout, 2016; Service & Kohonen, 1995). Strong evidence for a role of psychotypology in acquisition of novel vocabulary comes from studies of bilinguals learning a third language, where the language typologically closer to the target is used to support lexical access (i.e., utilising cognate forms to support communication; (Cenoz, 2003; Cenoz, Hufeisen, & Jessner, 2001; Hall et al., 2009; Hammarberg, 2001; Schepens et al., 2016). The potential for use of multiple languages gives rise to second effect called the L2 status effect, where the less proficient or later learned language may be used to scaffold communication, particularly in production tasks, or lapses in grammatical knowledge (Llama et al., 2010).

1.5.2.1 Form Similarity

Form similarity refers to features of individual words that appear similar to words in a known language. These effects are related to typological distance in that the perception of typological similarity or closeness is in part determined by the proportion of cognates and other features, like the phonotactic probability or phonological regularities, between languages (Bosma, Heeringa, Hoekstra, Versloot, & Blom, 2017; Hall et al., 2009; Schepens et al., 2016).

1.5.2.1.1 Phonotactic Probability

Phonotactic probability refers to the relative frequency of occurrence of phoneme sequences in a language (Gupta & Tisdale, 2009b; Jusczyk, 1986). Phonotactic probability is reflected at the whole word level in perception of wordlikeness for a given candidate in a given language (Frisch et al., 2000). Novel words that include phonological sequences more consistent with the phonotactic properties of a known language are easier to learn than words with inconsistent or incompatible phonotactic probabilities (Hoover et al., 2010; Stamer & Vitevitch, 2012, 2012; Storkel et al., 2006; Storkel & Hoover, 2010; Storkel & Maekawa, 2005), and are easier to recall in nonword repetition tasks (Vitevitch, 2002; Vitevitch et al., 1999; Vitevitch & Luce, 2005).Vitevitch and Luce (1999) proposed that the effects of phonotactic probability are routed in sublexical processes. Sublexical combinatorial processes are more efficient for novel words that align with known probabilistic properties of a language and therefore facilitate processing and integration.

1.5.2.1.2 Phonological Neighbourhood Density

Phonological neighbourhood density refers to the number of similar words in the lexicon that differ by a single phoneme. Neighbourhood density has different impacts on lexical processing depending on the task (Gupta & Tisdale, 2009b; Vitevitch & Luce, 2016). In speech perception tasks, dense phonological neighbourhoods result in phonological

interference effects and thus a slowing of recognition time in comparison to words from low density neighbourhoods. However, high phonological neighbourhood density facilitates word learning. Neighbourhood density is thought to occur at the lexical level such that for known words, cascaded lexical activation of phonological and semantic information create competition around potential candidate items for recognition. In learning, this cascaded activation strengthens associative links through partial activation of overlapping form and meaning (Storkel et al., 2006).

1.5.2.1.3 Formal similarity and cognates

Formal similarity is a highly salient cue to meaning (Ecke & Hall, 2014; van Hell & Tanner, 2012). Formal similarity refers to the degree of overlap of any two word forms. The phonological similarity of a novel word to known words is a particularly salient cue, especially in the absence of concurrent semantic information (Hall, 2002). Take the Spanish phrase "estoy embarazada"[I'm pregnant]. A beginner speaker of Spanish could be forgiven for thinking the interlocutor was embarrassed, although any consequent observations might produce an opportunity to learn the phrase "Me da vergüenza" [I'm embarrassed]. This is an example of the automatic cognate form assumption in action (e.g., Hall, 2002): phonological similarity leads to inferencing about the meaning of a word through cascaded activation of known words. In this case, embarazada would partially activate the stored phonological representation for embarrassed, leading to cascaded activation of the concept of embarrassment. In this situation, a false cognate has led the listener astray. However, in a vocabulary learning situation where the emphasis is on mapping to form to meaning, formal similarity can facilitate learning because of mutual supporting information between semantic and phonological levels elicited by partial activation of known words (Costa et al., 2000, 2005; Storkel et al., 2006). A number of word learning studies have demonstrated robust cognate facilitation effects such that phonologically similar translation equivalents are

learned more quickly and retained more robustly than non cognates (Bradley, King, & Hernandez, 2013; Carroll, 2012; De Groot & Keijzer, 2000; Ellis & Beaton, 1993a; Lotto & De Groot, 1998; Papagno & Vallar, 1992; Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010; E Service & Craik, 1993).

1.5.3 Cognitive Enhancers

In recent years, there has been an increased interest in the role of cognitive enhancers to improve word learning and memory, more generally. A series of studies have demonstrated that engagement in physical exercise can facilitate learning of novel vocabulary (Schmidt-Kassow et al., 2010, 2013; Winter et al., 2007). For example, Winter et al. (2007) demonstrated improved learning success immediately following a period of high intensity running. Immediate learning success was associated with an increase in brain-derived neurotrophic factor (BDNF), whereas medium, and longer term, retention was associated with greater increases in dopamine and adrenaline. Administration of Levodopa resulted in faster and more robust learning of a novel vocabulary in a study by Knecht et al. (2004). Similarly, Breitenstein, Korsukewitz, et al. (2006) administered a dopamine agonist or placebo to participants prior to learning a novel vocabulary over five days. The dopamine agonist impaired learning relative to the placebo group with depressed learning effects still observed at four-week follow-up. These studies demonstrate a critical role for dopamine in associative learning that may have implications for enhancement of learning and memory in general, and for rehabilitative practice. Additionally, dexamphetamine is another promising compound that has been shown to produce improvements in memory and learning in the short and medium term (Breitenstein, Flöel, et al., 2006; Whiting et al., 2007).

Alongside the rise in pharmaceutical products to enhance learning, other technologies have emerged that promise to improve our understanding of cognitive and neural function on the one hand, and to act as potential cognitive enhancer on the other. The re-introduction of

transcranial electrical stimulation techniques at the beginning of the last century (Nitsche &

Paulus, 2000; Priori, Berardelli, Rona, Accornero, & Manfredi, 1998) have seen an explosion

in their use as a tool to causally investigate brain-behaviour relationships non-invasively

(Dubljević et al., 2014). These techniques have great promise and reports demonstrate

enhanced cognitive performance in wide variety of domains, including word learning. The

next chapter provides an overview of the practical application and known mechanisms of

action for transcranial direct current stimulation (tDCS). A brief overview of the application

of tDCS to language production and language learning is provided and a rationale for the

study of dynamic language processing is presented as a framework for evaluating the role of

network-dependent effects in the manifestation of tDCS effects.

Running head: TDCS

Chapter 2: Transcranial Direct Current Stimulation: Overview and Application to Cognitive

Neuroscience of Language Processing

Transcranial Direct Current Stimulation: Overview and Application to Cognitive

Neuroscience of Language Processing

Current methods available for recording ongoing neural activity, such as event-related

potentials and functional magnetic resonance imaging, provide valuable insight into the

workings of the human brain. However, data from fMRI techniques in particular are

correlational in nature and do not necessarily permit causal interpretations (Paller, Lucas, &

Voss, 2012; Poldrack, 2006, 2011; c.f. Bressler & Seth, 2011; Farah, 2014; Machery, 2014).

The application of non-invasive brain stimulation (NIBS) techniques to the study of cognitive

neuroscience is unique in its potential for facilitating questions about the direct causality

between manipulation of neural functioning and its impact of behaviour. Combined directly

with observed data like event-related potentials, and performance on tasks, it is possible to

develop a greater understanding of the causal mechanisms that underpin behaviour and

function, within specific domains.

2.1 Non-invasive Brain Stimulation

2.1.1 Historical Application

Non-invasive brain stimulation has its roots in antiquity (for a comprehensive history,

Elliott, 2014). Roman physician, Scrobinius Largus, and later others like Galen and

Dioscordies wrote about the application of the electric torpedo fish for the relief of chronic

headache and other ailments (e.g., gout, anal prolapse; Kellaway, 1946). In the 11th century

Ibn-Sidah described the application of the torpedo fish for the treatment of epilepsy

(Kellaway, 1946; Priori, 2003). Following continued study of animal electricity and the

subsequent development of the voltaic pile by Alessandro Volta, Giovanni Aldini pioneered

the development of electrotherapy for the treatment of personality disorders and other

physical ailments (Parent, 2004). Transcranial electrical stimulation, and more broadly

electrotherapy, was widely adopted into medical practice throughout the 19th Century as a treatment for physical and psychological illness, as well as a tool to assess nerve damage and subsequent recovery. However, the rise of psychoanalysis and growing debate about the efficacy of electrotherapy in medicine resulted in a general loss of faith in the technique. With the development of electroconvulsive therapy (ECT) during World War I, and the dramatic and immediate impacts of this technique, low-amplitude electrotherapies were largely abandoned.

2.1.2 Early Electrical Stimulation in Humans

Before the turn of this century, relatively few reports of transcranially delivered electrical currents in humans existed. Direct cortical stimulation during neurosurgery was up until this point the only way of examining cortical stimulation of the human brain in vivo. In 1980, Merton and Morton published a paper successfully evoking responses from motor cortex through non-invasively applied electrical stimulation in humans. Very brief but high-voltage electrical pulses induced twitch-like responses in the fingers of the contralateral hand, face and foot, following stimulation over their respective sites in motor cortex. Moreover, Merton and Morton reported the inducement of visual phosphenes following stimulation of occipital visual regions, that changed position in the participants' visual field in a manner consistent with retinotopic organisation, although higher voltages were needed, which proved "quite painful" (Merton, Morton, Hill, & Marsden, 1982, p. 599; see also, Cracco, Amassian, Maccabee, & Cracco, 1989). In two early reports, very weak anodal stimulation at 0.3mA was shown to produce facilitation of response times in choice reaction time tasks (Elbert et al., 1981; D. Jaeger et al., 1987). Similarly, Korsakov and Matveeva (1983) reported reductions in psychophysical perception thresholds during 15-20minutes of 0.2mA anodal stimulation and showed direct modulations of evoked potentials in occipital and frontal regions, concurrent with behavioural changes. This is some of the first direct evidence that

even very low amplitude direct current passed through the scalp and into the brain can directly affect cortical function and subsequent behaviour. However, given the mixed protocols and limited yield of the technique at that time, transcranial electrical stimulation methods were put aside in favour of transcranial magnetic stimulation (TMS; (Barker et al., 1985), which showed more demonstrable physiological effects and utility for medical practice.

2.2 Modern Electrical Stimulation

At the turn of the century Priori, Berardelli, Rona, Accornero and Manfredi (1998) and Nitsche and Paulus (2000) introduced a low-amplitude, low-voltage electrical stimulation technique that could be delivered non-invasively in humans, with minimal discomfort and observable behavioural response. Relative to TMS, these devices are inexpensive (~£15,000), battery-powered and portable, and show potential for use as home treatment devices in clinical populations (e.g., Charvet et al., 2015). The perceived ease of the technique when it was first introduced and promising early results led to an exponential rise in the number of studies utilising tDCS (Dubljević et al., 2014). Dubljević et al. reported on 948 published studies of "transcranial direct current stimulation", "transcranial electrical stimulation" or "direct current brain polarisation" between 2006-2013. The number of publications has continued to increase year on year. An initial Title/Abstract search in Pubmed between 2006 and 2019, using Dubljević et al.'s search terms produced 3,153 hits as of 17th September 2019, without filtering or selection, but an estimate of 2,000-3,000 studies and reviews in that time is likely to be reasonable. Of the thousands of published studies on the topic, tDCS has been applied to a broad range of cognitive functions, including language processing (e.g., Price & Hamilton, 2015) and working memory (e.g., Mancuso, Ilieva, Hamilton, & Farah, 2016), as well as broad application as an adjunct to neurorehabilitation (Cappon et al., 2016). More recently however, the efficacy of tDCS for modulation of motor function and cognition

in healthy adults has been questioned. Several meta-analytic studies have failed to find evidence for a substantive improvement during or following active tDCS relative to sham. For example, (Horvath et al., 2015a) showed little-to-no effect of active tDCS versus sham for modulation of MEPs. In a second meta-analysis, the same authors (Horvath, Forte & Carter, 2015b), reported 59 analyses of tDCS studies conducted on a broad range of cognitive functions, none of which yielded a significant modulation of behaviour relative to sham. Considerable methodological issues with these meta-analyses were raised (Antal et al., 2015; Horvath, 2015; A. R. Price & Hamilton, 2015a) and subsequently contrasting findings from further meta-analytic reviews have arisen. For example, following re-analysis of the language studies included by Horvath et al. (2015b), Price, McAdams, Grossman and Hamilton (2015) reported a significant improvement in language processing abilities during and following anodal tDCS relative to sham. In contrast, Westwood and Romani (2017) reported a null effect of single session tDCS in their meta-analysis of naming and reading studies in healthy adults. Despite contradictory conclusions, meta-analyses on the topic of tDCS have clearly highlighted the considerable heterogeneity in stimulation protocols and the need for a more systematic investigation into the parameters that determine tDCS effects. Namely, the electrode montage, and the timing, intensity and duration of the stimulation.

2.3 Transcranial Direct Current Stimulation

The delivery of tDCS involves passing low amplitude constant current, in the range of 0.5 – 2mA, into the brain between two (or more) electrodes for up to 30minutes. A short ramp on/off of a few seconds is used to reduce artefacts like phosphenes, that can occur if current is turned on/off too quickly (Woods et al., 2016). In standard protocols, two rubber conductive electrodes, one anode and one cathode, are applied to the scalp and secured with a pair of rubber or non-absorbent, elasticated straps. The electrodes are inserted into sponge pouches moistened with an electrolyte solution of saline, to reduce impedance and discomfort

(Dundas et al., 2007), although conductive gel or paste (e.g., 10-20 paste) can be applied directly between the electrode and skin in combined tDCS-fMRI or tDCS-EEG studies (but see Palm et al., 2014). The application of tDCS is determined by key decisions about the electrode montage, the intensity and duration of the simulation, and the timing of stimulation.

2.3.1 Electrode Montage

Electrode size ranges between 9-100cm^2 and the choice for each electrode should be considered carefully in order to determine current density (Current density = A/m^2). Smaller electrodes will increase the current density, whereas larger electrodes (i.e., 100cm^2) become effectively inert as current is dispersed over a wide surface area. The focality of stimulation in a smaller electrode can be increased further by utilising a reference electrode with a larger surface area (Faria, Hallett, & Miranda, 2011; Nitsche et al., 2007). Selecting a site for the active electrode, given a desired effect and a known region of interest for a specific task, is relatively straight forward. However, greater consideration needs to be given to the choice of the reference site as even relative small changes in the position can alter current flow substantially (e.g., Bikson, Datta, Rahman, & Scaturro, 2010) and behavioural outcome (Moliadze et al., 2010; Penolazzi et al., 2013). The choice of the relative position of the electrodes in a montage is important for a three reasons: 1) the current density entering the brain decreases with increasing distance between electrodes, 2) the choice between cephalic and extra-cephalic reference sites can more or less complicate the interpretation of the results and 3) small differences in relative position of the electrodes can have a marked impact on the current flow and subsequent outcome of stimulation. Most studies utilise a contralateral supraorbital reference site, consistent with early studies of motor function, with the active electrode (anode or cathode, depending desired outcome) centred over a region of interest for a task or outcome. In other studies, homologues of the target region are included as the reference site to modulate the inter-hemispheric balance across hemispheres. However, the

inclusion of a cephalic reference site can complicate the interpretation of the outcome as the relationship between current polarity and outcome is obscured. To combat this, a growing number of authors have begun adopting extra-cephalic reference sites, commonly the cheek, upper arm or leg. There may be concerns in some of these cases that current flow may traverse the brainstem, but these montages appear to be safe (Vandermeeren et al., 2010). However, there is a need for more detailed examination of different montages in specific tasks, whilst holding intensity and duration constant.

2.3.2 Intensity and Duration

As well as the relative position and size of the electrodes, the total duration of stimulation should also be considered to determine the charge [$C = mA/1000 \times time(s)$] in order to calculate the charge density delivered to ensure participant safety (charge density = C/m^2; Liebetanz et al., 2009; Nitsche et al., 2008; Woods et al., 2016). In common protocols utilising 1-2mA stimulation, for 20minutes, via 25-35cm^2 electrodes, both the current (0.29-0.80 A/m^2) and charge densities (343-960 C/m^2) fall two orders of magnitude below levels that may begin to cause tissue damage (142.9 A/m^2; 52,400 C/m^2; Liebetanz et al., 2009; Matsumoto & Ugawa, 2017).

Initial studies examining the intensity and duration of tDCS effects were conducted in the motor domain and these parameters have been readily extracted and applied across the whole field of tDCS. However, the effect of the intensity and duration of stimulation on behavioural outcomes are not straight forward even in the motor domain. Stimulation at 1mA for around five minutes resulted in significant MEP changes for up to 20 minutes (Nitsche & Paulus, 2000), whilst 9 minutes or more of stimulation produced after effects observable for up to an hour (Nitsche et al., 2005; Nitsche, Nitsche, & Klein, 2003). In many studies of cognition, stimulation intensity was increased to 2mA under the impression that more intense stimulation would produce a greater impact on cognitive performance. For example, Iyer et

al. (2005) reported that verbal fluency performance significantly improved after 2mA offline stimulation over left DLPFC regions but not after 1mA tDCS. However, most studies in cognition did not make this first step in determining the outcome of increased stimulation and for most tasks it is unclear what the optimal parameters should be. In response to the rise of cognitive studies utilising higher current amplitudes of 1.5mA to 2mA, Batsikadze, Moliadze, Paulus, Kuo and Nitsche (2013) showed that the effects of stimulation produced non-linear changes in MEP responses following stimulation of motor cortex. Cathodal tDCS at 1mA resulted in a decrease in MEP amplitudes but at 2mA the effects were reversed – MEP amplitude increased, relative to sham. Moreover, the size of MEP changes and duration of effects under 2mA anodal stimulation were no greater than those observed at 1mA in previous studies. More recent reports have questioned the generalisability of these parameters to the study of more complex cognitive networks (Marian E. Berryhill et al., 2014; Jacobson et al., 2012).

2.3.3 Timing

TDCS can be delivered online, concurrently with a task, or offline, without a concurrent task. Only very few investigations in the literature that directly compare the effectiveness of online versus offline tDCS in motor or the cognitive domain (Fertonani, Brambilla, Cotelli, & Miniussi, 2014; Martin, Liu, Alonzo, Green, & Loo, 2014; Nitsche et al., 2007; Pirulli, Fertonani, & Miniussi, 2013; Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008). The optimal timing may differ depending on the task and the cognitive network being investigated. However, there is reason to believe that online tDCS may be preferable to offline protocols. tDCS produces only weak changes in resting membrane thresholds and therefore is most likely to impact on neurons that are close to firing threshold (e.g., Bikson & Rahman, 2013). The assumption underlying online tDCS is that by engaging a specific network it may become more susceptible to modulation by electrical

stimulation, capitalising on ongoing Hebbian plasticity, enhancing long-term potentiation or depression (e.g., Bikson & Rahman, 2013; Miniussi, Harris, & Ruzzoli, 2013). Some authors have suggested that this may render online approaches particularly useful in learning protocols (e.g., Miniussi et al., 2013). In treatment studies online tDCS applied in conjunction with cognitive training produces the greatest functional improvements in adults following stroke (Cappon et al., 2016; Crinion, 2016; Holland & Crinion, 2012; Miniussi et al., 2013). In healthy adults, online anodal tDCS more consistently results in modulation of learning performance. For example, Stagg et al., (2011) reported modulation of motor sequence learning in a polarity specific manner with online stimulation: online anodal tDCS facilitated learning, whereas online cathodal tDCS inhibited learning. Offline stimulation resulted in slower and less successful learning irrespective polarity but neither online or offline affected simple reaction time performance. Similarly, Martin et al. (2014) reported enhanced skill consolidation during working memory training under online compared to offline conditions. In performance based tasks, online tDCS may produce the most consistent effects across age groups. Fertonani et al. (2014) engaged groups of healthy younger and older adults in naming tasks conducted online or offline with 2mA anodal tDCS applied to left DLPFC regions. Younger adults showed facilitation of naming response times in both online and offline conditions but older adults showed an improvement only in the online condition. However, Pirulli et al. (2013) reported enhancement of perceptual learning following offline anodal tDCS applied to occipital cortex relative to sham but no improvement during online tDCS. This finding suggests that the impact of timing is likely to depend on the task demands and cognitive domain under study.

2.3.4 After Effects and Blinding

Within the recommended parameter space (see Bikson et al., 2016; Woods et al., 2016), transcranial electrical stimulation is safe, non-invasive, and has not been associated

with any serious side effects (e.g., seizure). However, participants commonly report mild to

moderate itching, tingling and heating sensations under the electrodes during stimulation

(Bikson et al., 2012, 2016; Fertonani et al., 2015; Minhas et al., 2011; Poreisz et al., 2007).

Side effects such as headache, nausea or burns/skin irritation are rare (Nitsche et al., 2008).

These perceptible side effects present a need for an effective sham protocol to rule out

possible novelty and demand characteristics of participants.

The most common approach to blinding participants to stimulation conditions is to

administer 30s of stimulation at the beginning of the session, with a short ramp up and down

of current. At 1mA, Gandiga, Hummel and Cohen (2006) reported effective blinding using

this method but the effectiveness of this approach has been questioned, for amplitudes as low

as 0.4mA and particularly at higher amplitudes exceeding 1mA (Ambrus et al., 2012; André

Russowsky Brunoni et al., 2014; Fertonani et al., 2015; Greinacher et al., 2019; Kessler et al.,

2012b; Minhas et al., 2011; O'Connell et al., 2012; Palm et al., 2014; Russo et al., 2013;

Wallace et al., 2016). Other possibilities are to utilise ultra-low current densities of 0.1mA,

where insufficient current enters the brain to cause a physiological effect (Clark, Coffman,

Trumbo, & Gasparovic, 2011). Whilst others have applied an brief period of stimulation at

the beginning and end of the stimulation period (Lukasik et al., 2018). However, assessment

of the effectiveness of sham protocols in empirical studies in general is difficult because of a

consistent lack of assessment and underreporting of after effects (Brunoni et al., 2011).

2.3.5 Physiological Mechanisms

Despite the 2,000-3,000+ studies utilising the technique, the exact physiological

mechanisms of tDCS are unclear. Some studies report that up to 50% of the delivered current

passes into the brain (Miranda, Lomarev, & Hallett, 2006; Nitsche & Paulus, 2000; Nitsche et

al., 2008). A 2mA current with a current density of 0.22 mA/cm^2 results in a 0.1mA/cm^2

current density in cortex (Miranda et al., 2006), which is calculated to be of a sufficient

magnitude to alter the resting membrane threshold of neurons in the path of current flow (Bindman et al., 1964; Creutzfeldt et al., 1962). At this level, current densities are not sufficiently strong to cause action potentials. Thus, tDCS is thought to act at subthreshold levels, altering the ionic balance within neurons, increasing or decreasing the likelihood that neurons close to threshold will fire.

The effects of tDCS are thought to be polarity-specific. Priori, Berardelli, Rona, Accornero and Manfredi (1998) and Nitsche and Paulus (2000) published the initial reports which demonstrated that anodal current resulted in larger MEP amplitudes, whereas a cathodal current resulted in a relative reduction in amplitude. In Nitsche and Paulus, the amplitude of MEP changes increased with increasing current amplitudes (from 0.2 – 1mA) and out-lasted stimulation by 4-5 minutes before returning to baseline levels. In a series of follow-up studies, Nitsche and colleagues repeatedly demonstrated such polarity specific effects, albeit in relatively small samples. Moreover, this research group demonstrated the observed excitability effects resulted from changes in resting membrane thresholds, which following prolonged stimulation (~ 5 minutes) altered the rate of membrane depolarisation and synaptic transmission, which may contribute to the after effects of tDCS, observed up to an hour after stimulation (Lang, Nitsche, Paulus, Rothwell, & Lemon, 2004; Liebetanz, Nitsche, Tergau, & Paulus, 2002; Nitsche, Nitsche, & Klein, 2003; Nitsche et al., 2005). These data suggest a role for tDCS for the modulation of long-term potentiation and long-term depression effects. The findings in humans tally with direct stimulation studies in rats that show prolonged changes (up to 72 hours) in calcium concentrations after 30 minutes of anodal polarisation at the target and in connected regions of the hippocampus and thalamus, and are dependent on NMDA receptors (Islam, Aftabuddin, et al., 1995; Islam et al., 1994; Islam, Moriwaki, et al., 1995).The notion of LTP/LTD-like changes in humans induced by tDCS has also gained further support from studies demonstrating site and polarity specific

modulation of metabolite concentrations, including GABA, myoinositol and combined

glutamate and glutamine (glx), as measured by proton magnetic resonance spectroscopy

(Clark, Coffman, Trumbo, & Gasparovic, 2011; Kim, Stephenson, Morris, & Jackson, 2014;

Rango et al., 2008; Stagg et al., 2009, 2011), as well as changes in functional connectivity

and resting-state fMRI (Keeser et al., 2011; Meinzer et al., 2012; Peña-Gómez et al., 2012).

In this vein, positive-going current is assumed to result in excitation of cortex under

the anode and inhibition of cortex under the cathode (herein the AeCi doctrine).

Consequently, the AeCi doctrine was translated in to studies of cognition. However, the AeCi

approach does not appear to generalise to current amplitudes greater than 1mA, nor does it

affect cognitive performance in a manner consistent with this perspective. In 2012, Jacobson,

Koslowsky and Lavidor (2012) published a meta-analysis that demonstrated relatively

consistent reports of AeCi modulation in motor studies but contrasting or contradictory

effects in cognition. Although, anodal tDCS generally resulted in improved performance in

perceptual and cognitive tasks, cathodal stimulation rarely produced the expected inhibition

effects. Of the five studies on language assessed, none reported a cathodal inhibition effect.

In fact, Monti et al. (2008) reported *facilitation* of picture naming accuracy in eight people

with aphasia, although differences in physiology due to lesions may have altered current

flow. Berryhill, Peterson, Jones and Stephens (2014) conducted another review, primarily

focused on studies of working memory and came to similar conclusions, highlighting the

roles of low power, task difficulty, sample characteristics, and protocol heterogeneity as

potential moderators of tDCS effects.

From these observations the AeCi account is too simplistic. The assumption that

effects observed in the motor system translate to the cognitive domain is not supported by the

data, and a more nuanced view of the potential mechanisms of action is needed. One reason

why these effects might not translate so easily from motor cognitive domains may be due to

the complexity of the ongoing activity within the network under study. The operations involved in any aspect of cognition are underpinned by complex interactions between and within widely distributed networks. In fMRI studies, focal effects of tDCS in a task-specific region suggest an interaction with ongoing activity. Moreover, these localised effects likely reflect modulations of network-wide connectivity as demonstrated in several functional connectivity studies (Keeser et al., 2011; Marcus Meinzer et al., 2012; Peña-Gómez et al., 2012; Polanía et al., 2011). For example, Meinzer et al. (2012) delivered 1mA anodal tDCS over left IFG regions during a semantic word generation task, in 20 healthy adults, completed whilst in an MRI scanner. fMRI results demonstrated a significant reduction in task-related activity in the left ventral IFG, a region critical for successful semantic retrieval, as well as increased functional connectivity between distal regions of the language network. These data suggest a complex interaction between the ongoing network state and the electric field induced by tDCS. Moreover, the spatial and temporal resolution of tDCS is extremely low under traditional setups and the electric field that passes between the electrodes stimulates all tissue between them. Current is often applied up to 30minutes within a single session and therefore the effects of tDCS are more likely to impact whole networks of connected regions rather than at any one specific node/region under electrode sites (Fertonani & Miniussi, 2017). It is likely that studies demonstrate "site-specific" changes in activity during tDCS are driven by task-dependent changes in LTP and modulation of activity within the whole network (e.g., Bikson & Rahman, 2013).

2.4 Network State-Dependency and Stochastic Resonance

State-dependency refers to the idea that the effects of stimulation will be dependent upon the relative activity within a neuronal population of interest. This term was first introduced in the TMS literature. Although many previous TMS studies had supported the 'virtual lesion' approach to disturbing cortical function, counterintuitive findings of

facilitation suggested moderation of TMS effects, dependent on the state of the network under study. State-dependency of TMS for the modulation of perception and cognition was first clearly demonstrated by Silvanto, Muggleton, Cowey and Walsh (2007). In their first experiment, participants engaged in visual adaptation to single or dual colour conditions, before receiving 15 pulses of TMS designed to induce phosphenes. Phosphenes induced before TMS were colourless, but following adaptation phosphenes were reported as the same colour as the adaptation stimulus. In a second experiment, Silvanto and colleagues engaged participants in a psychophysical task that required adaptation to gratings of a specific orientation and colour. Without stimulation, participants were significantly worse at detecting gratings congruent with the adaptation stimulus (e.g., red-black, 45º right) compared to those incongruent with the stimulus (e.g., green-black, 45º left). Following TMS, detection rates were comparable between congruent and incongruent conditions. In both cases, Silvanto et al. concluded that TMS facilitated the firing of the least active neurons with the overlapping regions coding for colour. Adaptation reduces the firing rate of specific neuronal populations involved. Silvanto et al. argue that TMS alters the signal-to-noise ratio by increasing the noise around the signal, a perspective inline with stochastic resonance accounts that suggest non-linear effects of brain stimulation on function (Fertonani & Miniussi, 2017; Miniussi et al., 2013; Silvanto et al., 2008; Walsh & Pascual-Leone, 2003).

Stochastic resonance refers to the idea that activity in an area surrounding target neurons will be in some way related or correlated to the target signal. In a non-linear system like the brain, injection of a small amount of noise can substantially alter the outcome. Miniussi et al. (2013) propose that stochastic resonance can be applied to the interpretation of the effects of online tDCS during cognitive task performance. tDCS adds noise into task-related activity and that response to tDCS will depend on the coherence of that activity, or the relative signal-to-noise ratio; it is state-dependent. Expanding on this idea it is possible to

imagine that in a neuronal population with low signal-to-noise, activity related to the task-goal is weak and swamped by noise. Inducement of additional noise with tDCS is likely to boost both the signal and the noise and produce little in the way of improvement for the target. If signal-to-noise is high and target activity is already optimal then tDCS will likely result in an increase in the neuronal population that fires for noise, reducing the signal-to-noise level, resulting in no change, or worse performance. The ideal situation under this account is in a neuronal population with a moderate signal-to-noise, where target activity is winning out, but barely in normal circumstances. In this case, tDCS-induced shifts in firing rates for both target and noise will result in a subtle improvement for the target as its signal is strengthened by a) the goal-directed stimulus b) the coherence of the firing rates for neurons coding for noise and c) the effects of stimulation. Unlike TMS, tDCS acts at the subthreshold level and is more likely than TMS to be impacted by ongoing neuronal activity. Furthermore, one must consider that the effects of tDCS, and current is dispersed widely to all cortex in the path of current flow. Miniussi et al. (2013; see also Fertonani & Miniussi, 2017) therefore proposed that tDCS effects should be considered as network-state dependent, rather than simply dependent on the state of a specific population of neurons, as per TMS. From this perspective, site-specific modulations observed in fMRI studies reflect an interaction between the ongoing activity within task-relevant networks, and help to provide a functional account of increased functional connectivity following online stimulation (Keeser et al., 2011; Kunze et al., 2016; Marcus Meinzer et al., 2012; Peña-Gómez et al., 2012). Given that current spreads throughout the brain and effects are observed downstream from the target site, the effects of tDCS are likely to be more strongly affected by the ongoing network activity as well as dependent on the state of the target neural population. This framework, although not a mechanistic account of the physiological effects, can be applied to interpret the outcome from tDCS studies at various levels (molecular, network, task) and help to explain inconsistency of

results under the AeCI doctrine (e.g., Jacobson et al., 2012). Moreover, the idea of network-state dependency implies influences from participants' baseline states, as well as task-induced and stimulus-induced modulations of network function, that may interact in complex ways. Understanding how these factors might moderate tDCS effects and vice versa is important in advancing our understanding of the functional effects of tDCS and in evaluating theories about cognitive processes.

2.5 Language Processing and tDCS

The language network provides a potential canvas for the study of network-state dependent effects of tDCS. By its very nature, language processing is complex, is distributed in nature and ongoing functional is dynamically modifiable by task and stimulus characteristics. Because of the centrality of language to human function and thought, ample time and effort has been invested in explaining key processes of language processing in the production and comprehension domains. Development of norms for myriad lexical factors enable careful control of stimulus characteristics and good prediction of participant responses to key variables, in well-developed tasks. For example, psycholinguists would expect relatively consistent effects of lexical frequency between participants during picture naming, or strong facilitation effects in repetition priming studies. Manipulation of specific task and stimulus-level factors can be utilised to modulate the state of an individual's language network, paving the way for specific examination of network-state dependency effects of tDCS, whilst providing insight regarding mechanisms of action in language processing.

In particular, the application of tDCS to language processing shows promise for development of a tool to be used as an adjunct for aphasia therapy. Crinion (2016) highlighted that tDCS combined with an effective rehabilitative technique may enhance the treatment effect, such that consolidation of therapy gains may be improved. Despite the rise in its application treatment of aphasia, particularly for the amelioration of production deficits,

there is considerable variability in response to tDCS and language therapy alone. The combined efficacy of these techniques still requires evaluation and systematic review of key factors, like the extent and nature of brain damage, the residual level of function in the domain of interest, and activation within areas preserved following brain damage, as well as more general individual differences. Optimal protocols for application of tDCS in aphasia, and more generally for neurorehabilitative use, are a long way off (e.g., Cappon et al., 2016; Elsner et al., 2015). Understanding how tDCS interacts with the intact language network and ongoing processing in healthy adults may provide insight for the optimisation of treatment protocols. In the chapters that follow, a detailed overview of the most pertinent studies are discussed but a brief summary of the effects of tDCS on language processing in healthy adults is outlined below.

2.5.1 tDCS and Language in Healthy Adults

The application of tDCS to language processing has focused most frequently on three aspects of language processing: verbal fluency, naming, and word learning. The primary focus of this thesis is on naming and word learning and this is the focus of the summaries below.

2.5.1.1 Naming

TDCS Studies of naming have utilised two types of task: confrontation naming or semantic interference. Confrontation naming requires participants to name an object from a picture in isolation on presentation, as fast an accurately as they can. Semantic interference tasks require confrontation naming but stimulus sets are manipulated to include objects from the same semantic families or presented in heterogeneous sets of unrelated objects. On each presentation of a category exemplar (lag 0 = "dog", lag 1 = "cat"), response latencies increase by approximately 30ms on average, indexing potential competition or increases in activation of semantically related competitors (e.g., Howard, Nickels, Coltheart, & Cole-Virtue, 2006).

The predominant finding in this literature is an effect of anodal tDCS on the effect of interest. In confrontation naming studies, anodal tDCS has been shown to result in facilitation of naming response times following application to left IFG (Holland et al., 2011), left STG (Sparing et al., 2008) and left DLPFC regions (Fertonani et al., 2010, 2014; Wirth et al., 2011). Cathodal stimulation appears to have little to no effect on confrontation naming in left hemisphere sites, although this approach was successful in reducing inter-hemispheric competition when applied to the right homologue of Broca's area (Rosso et al., 2014). However, there is considerable heterogeneity between studies in terms of stimulation protocols and task make-up, which limit interpretability and stability of these effects (Klaus & Schutter, 2018; Westwood & Romani, 2017). In semantic interference studies, anodal tDCS applied to left STG appears to increase semantic competition between category exemplars, leading to larger semantic interference effects (Meinzer, Yetim, McMahon, & de Zubicaray, 2016). However, effects of tDCS applied to frontal sites are more variable, with some studies demonstrating reduced SI effects, whilst others show limited efficacy of tDCS over these sites.

Despite a considerable number of studies applying tDCS as an adjunct to naming treatments in aphasia, there is very little consensus on the parameters that determine success of tDCS for the modulation of naming behaviours in healthy adults. Understanding the nature of these effects may help to enhance understanding of how tDCS interacts with the language network to affect naming performance and ultimately contribute to the improvement of rehabilitative protocols. Thus far, no study has directly compared the effect of tDCS on naming at multiple sites, in the same task, in samples of similar participants. Additionally, the timing of stimulation varies between studies and there has been only one direct comparison of the effects of online and offline stimulation in confrontation naming (Fertonani et al., 2014). Moreover, the potential interaction of stimulation timing with word-level activation state may

be of critical importance in identifying optimal network states for maximal improvement in

naming performance. The aim of the study reported in chapter 3 was to examine these factors

in more detail.

2.5.1.2 Word Learning

Another area of language processing that has received considerable interested is word

learning. Word learning tasks have parallels with mechanisms of relearning employed in

rehabilitative techniques in aphasia (Breitenstein & Knecht, 2002; Raboyeau et al., 2008;

Gaëlle Raboyeau et al., 2004). The findings and protocols employed in the handful of studies

that have examined the effects of tDCS on word learning in healthy adults have been

reasonably consistent, in contrast to naming studies. All tDCS studies of word learning to

date have employed protocols with consistent current density of 0.028 (mA/cm^2) with the

anode centred over the left pSTG region and cathode over right supraorbital regions (Fiori et

al., 2011; Flöel et al., 2008; Marcus Meinzer et al., 2014; Savill et al., 2015), with the

exception of (Liuzzi et al., 2010) who examined verb learning specifically. Posterior STG and

inferior parietal cortex are thought to underpin phonological lexical (Buchsbaum et al., 2001;

Hickok & Poeppel, 2007; Peramunage et al., 2010; Prabhakaran et al., 2006) and

phonological working memory abilities (Graves et al., 2008; Leff et al., 2009; Okada &

Hickok, 2006) a skill critical for learning new words (e.g., Gupta & Tisdale, 2009a). Anodal

stimulation over posterior temporal-parietal regions has resulted in significant gains in word

learning relative to sham and cathodal stimulation, where this latter condition has been (Flöel

et al., 2008). Most studies have utilised single session protocols (cf. Meinzer et al., 2014 for

five-session protocol) and focused on short or medium term consolidation effects with limited

examination of longer-term follow-up (e.g., after a week without exposure). In Flöel et al.

(2008) better learning was achieved under anodal tDCS and translation recognition

performance was better compared to sham and cathodal conditions immediately following

stimulation, although the learning advantage was no longer significant a week post-stimulation.

Despite relative convergence of results from a small number of studies, some open questions remain. First, all word learning studies using tDCS have utilised novel pseudowords derived from the native language of participants paired with familiar and/or unfamiliar objects. Native-language derived pseudowords will conform to the phonotactic rules of that language and may not reflect the similarities and differences between two different languages that strongly influence participants' learning success and ability to draw on top-down knowledge. It is currently not clear whether the effects of tDCS reported thus far would generalise to real foreign language learning. Additionally, this begs the question of whether the similarity of novel words would moderate the effect of tDCS. Under the network-state dependency account, the response of a neuronal population highly activated by highly similar incoming phonological information would presumably differ substantially to neuronal activation to highly dissimilar phonological information. Second, the response to tDCS is highly variable and depends on myriad participant factors. One consideration is baseline characteristics and abilities of participants that would impact of the response of a network to a given task. One of the key determinants for successful word learning is high phonological working memory abilities and this relationship has been consistently observed amongst children and adults. Participants' abilities in this domain are likely to impact on the pattern of activity in the network during learning, which may moderate the effects of tDCS. One other major determinant of word learning success if prior experience of multiple languages. A growing body of work has demonstrated a consistent advantage in novel word learning for bilinguals relative monolinguals (Kaushanskaya, Yoo, & Van Hecke, 2013; Margarita Kaushanskaya, 2012; Margarita Kaushanskaya & Marian, 2009b; Costanza Papagno & Vallar, 1995; van Hell & Mahn, 1997). Processing of incoming speech

information is accomplished in a broadly similar manner for monolinguals and bilinguals but bilingual experience changes the response in the language network in complex ways, yet to be fully understood. One of the original aims of this thesis was to examine how bilingual experience might alter the response to tDCS. During the study reported in Chapter X, it became apparent that recruitment of a second bilingual sample of a sufficient size would not be possible in the time available.

In chapters 6 and 7, two studies are reported that attempt to address questions around state-dependent effects on learning. Chapter 6 is a write-up of a study testing for a bilingual advantage in associative learning of novel Dutch words. Additionally, we examined whether phonological working memory abilities can account for this advantage and tested for moderating effects of bilingual switching experience on learning and translation performance. Chapter 7 utilises the same learning protocol paired with online active and sham tDCS in a sample of monolinguals. This study aimed to test for improvement in word learning and/or translation performance under anodal stimulation conditions and tested for moderating effects of phonological working memory performance.

Chapter 3: tDCS Facilitation of Picture Naming: Item-specific, task general, or neither?

3.1 Abstract

The aim of the present study was to clarify the conditions under which anodal tDCS applied to left hemisphere language sites may facilitate picture naming latencies in healthy young adults. We built upon previous studies by directly testing for item-specific and generalised effects of tDCS through manipulation of item-familiarisation and through testing for both online and offline effects of stimulation, in the same paradigm. In addition, we tested for the robustness of these effects by comparing two left hemisphere sites critical for lexical retrieval. Twenty-eight healthy young adults completed two testing sessions receiving either anodal (1.5mA, 20mins) or sham stimulation (1.5mA, 30s) in each session. Half of the participants received tDCS over the left inferior frontal region and the other half over the left posterior superior temporal region. All participants were asked to a name a set of pictures and their response latencies were compared at three time points (before, during and after the end of stimulation). The stimulus set was constructed so that some items were presented at all time points, some before and after stimulation, and some during stimulation only. A parsimonious linear mixed effects model revealed robust repetition priming effects as latencies were reliably faster for previously named items in all conditions. However, active tDCS did not produce any additional facilitation in relation to sham, and even led to slower performance in the IFG group when the stimulated items differed from those tested at baseline and post-test. Our findings add to the present debate about the efficacy of single-session tDCS for modulation of lexical retrieval in healthy young adults. We conclude that future research should take a more systematic, step-wise approach to the application of tDCS to the study of language and that more sensitive experimental paradigms, which include a training element, are more adapted to the study of cognitive processes in populations with optimal levels of cortical excitability.

3.2 Introduction

The goal of the present study was to test whether transcranial direct current stimulation (tDCS) effects on confrontation naming in healthy young adults reflect task general or item-specific effects. We aimed to gain a better understanding of how stimulation site and stimulus presentation may interact with expected online and offline effects of tDCS – namely facilitation of RTs – in line with previous reports. Observing either item-specific or task-general effects would shed light onto the nature of state-dependent effects of tDCS and provide potential insight for application to treatment paradigms.

Transcranial direct current stimulation is a safe non-invasive brain stimulation technique that has grown increasingly popular as a cognitive neuroscience technique over the past two decades (Dubljević et al., 2014). Compared to other neuroscience techniques (e.g., TMS, fMRI), tDCS is comparatively inexpensive, it is portable, and the proposed mechanisms of action are potentially applicable to multiple domains of cognition and neurorehabilitative treatments (e.g., Cappon, Jahanshahi, & Bisiacchi, 2016). In commonly used setups, weak, constant currents (1 – 2mA) are passed into the brain via two (or more) electrodes applied to the scalp for up to 30 minutes (for technical overview: Woods et al., 2016). Neurons in the path of current flow are thought to be affected in a somewhat polarity specific manner. Anodal (positive) stimulation results in relative depolarisation, increasing the likelihood that the neurons will fire, whereas cathodal (negative) stimulation, would hyperpolarise the resting threshold, decreasing firing rates. Applied to task-critical regions, tDCS is thought to increase or decrease the likelihood of long term potentiation/depression, offering the potential to directly manipulate Hebbian plasticity, critical for skill enhancement and rehabilitation (Murphy & Corbett, 2009).

There is increasing evidence that tDCS can be an effective adjunct to behavioural methods in the cognitive rehabilitation of neuropsychological conditions such as aphasia

(e.g., Vallar & Bolognini, 2011) . However, the efficacy of tDCS for manipulation of cognition in healthy adults is less clear (Horvath, Forte, & Carter, 2015; Klaus & Schutter, 2018; Price, McAdams, Grossman, & Hamilton, 2015; Westwood & Romani, 2017). Considerable methodological variability between studies of similar cognitive processes and limited investigative work regarding critical parameters within specific cognitive domains, has contributed to the growing perception that tDCS may be unreliable. Protocols applied to the study of higher-order cognition are extrapolated from studies of the motor system that may not translate in a straightforward manner (Marian E. Berryhill et al., 2014; Jacobson et al., 2012). The myriad factors that are likely to affect behavioural outcomes in tDCS studies (e.g., timing, stimulation sites, individual variability) are still poorly understood (for discussion Krause & Cohen Kadosh, 2014).

One area that has been subject to considerable debate is the study of language processing in healthy adults. In a broad meta-analysis of single session tDCS studies of cognition, Horvath, Forte and Carter (2015) concluded there was no reliable effect of tDCS in any domain, including language. However, their methodology was criticised (Antal, Keeser, Priori, Padberg, & Nitsche, 2015; Price & Hamilton, 2015; cf. Horvath, 2015). A re-analysis by Price, McAdams, Grossman and Hamilton (2015) demonstrated significant positive effects of tDCS immediately following the stimulation period. One difficulty in interpreting these data is that there is considerable variability between studies, not only in terms of tDCS methodology, but also in terms of the specific language processes being investigated.

The present study focused on the effect of tDCS on word retrieval during confrontation naming in healthy, young adults. Picture naming tasks are commonly administered to probe lexical retrieval in healthy adults and as a focus for remediation of anomia in aphasia. Although picture naming is a simple task, it does involve a complex set of processes. Following visual analysis, the semantic features of a concept are activated from

the picture, and in turn activate the lexical representation of the corresponding word form, before activation of phonetic features and motor programmes for production (e.g., Rapp & Goldrick, 2006). The accuracy and speed of confrontation naming is highly variable across individuals, and is influenced by factors such as age, level of education and age of acquisition of the test language (e.g., Tombaugh & Hubiey, 1997). Naming performance also varies across items as a function of a number of factors such as lexical frequency, name agreement and semantic density (e.g., Alario et al., 2004; Rabovsky, Schad, & Abdel Rahman, 2016). In addition, it is widely accepted that activation of a set of semantic features leads to the activation of not only the best match lexical representation but also to a larger set of semantically related words, resulting in a noisy selection process (e.g., Oppenheim, Dell, & Schwartz, 2010). In principle, applying anodal tDCS to cortical sites critical for lexical retrieval (e.g., left IFG, left STG; Price, 2012) during a skilled task like naming will result in suppression of noise and maximise the signal for selection of the correct object naming, leading to facilitation of naming responses (Miniussi, Harris, & Ruzzoli, 2013, p. 1707).

Although much of the literature regarding tDCS and word retrieval has focused on semantic interference paradigms (for critical review, Meinzer, Yetim, McMahon, & de Zubicaray, 2016), several studies on confrontation naming in healthy adults have reported faster responses following anodal tDCS applied to left-hemisphere sites (cf. Rosso et al., 2014 for cathodal over right IFG). Sparing, Dafotakis, Meister, Thirugnanasambandam & Fink (2008) published the first tDCS study of picture naming. They observed facilitation immediately following the cessation of online anodal stimulation applied to left posterior temporal regions (e.g., Wernicke's area), However, RTs returned to baseline by five minutes post-tDCS. In another study, Fertonani, Rosini, Cotelli, Rossini and Miniussi (2010) explored the effect of offline stimulation (stimulation without a concurrent task) applied to left dorsolateral pre-frontal cortex (DLPFC, 2mA) before the administration of an object and

action naming task. RTs were faster immediately following anodal stimulation, as compared

to cathodal and sham but facilitation was not specific to grammatical class. In a follow-up

study utilising the same object-action naming task and stimulation site, Fertonani, Brambilla,

Cotelli and Miniussi (2014) compared the effect of online and offline stimulation, in younger

and older adults. In older adults, facilitation was observed in the online protocol only. In

younger adults, both online and offline stimulation led to faster responses. However, in Wirth

et al., (2011) picture naming facilitation in young adults was observed during online

stimulation of the DLPFC but not offline. Taken together these findings support potential

reproducibility of tDCS effects on picture naming (see also Klaus & Schutter, 2018) although

these effects might be short-lived and limited to on-line protocols. Online stimulation may

promote plasticity for task-specific processes, enhancing LTP/LTD in a direct way – so-

called state-dependency (Miniussi et al., 2013; Silvanto et al., 2008), a rationale that is

prevalent in anomia treatment studies (for review, Crinion, 2016). In contrast, offline

protocols may have a broader effect on cortical 'readiness' prior to task performance,

resulting in general up-regulation of processing.

Despite these positive reports, a recent meta-analysis of word retrieval studies in

healthy participants concluded that the effects of tDCS are not statistically reliable

(Westwood & Romani, 2017) whatever the stimulation site or protocol. It also highlighted

that a publication bias for positive findings may have led to an over-estimation of the

influence of tDCS on cognitive processing. Consistent with this view, the same research

group failed to observe any effects of tDCS across four word retrieval experiments

(Westwood, Olson, Miall, Nappo, & Romani, 2017; but see Gauvin, Meinzer, & de

Zubicaray, 2017).

Nevertheless, it is probably too soon to abandon the paradigm altogether. As we have

seen, it is difficult to compare studies directly as they vary on multiple dimensions, some of

which may be determinant. In addition to the stimulation parameters themselves (e.g.,

intensity, duration, electrode placement), there are variations in important aspects of the

design of different studies that have not been systematically evaluated. Amongst these, some

key factors are 1) the stimulation sites, 2) whether the stimulation is delivered on-line vs. off-

line (i.e., during vs. before the execution the task assessed), 3) when potential changes in

performance are assessed (i.e., in relation to a baseline or not, during vs. post-stimulation,

how long after stimulation), 4) whether the study measures changes within-participants or

across groups (active vs. sham). In addition, an important factor concerns the specificity of

the expected effects of tDCS stimulation: should facilitation be restricted to specific trained

words or would one expect to observe a more global improvement in lexical retrieval

performance, generalising across items and possibly tasks? Prior studies do not inform this

issue as they either presented the same items in each of the conditions (Holland et al., 2011)

or else provided over-training before naming; Sparing et al., 2008) with the aim of reducing

variance prior to stimulation. In the absence of a condition specifically designed to assess

generalisation (cf. (Fertonani et al., 2010, 2014) for a general effect of tDCS to action and

object naming), positive results (when they occur) are equally compatible with the hypothesis

of item-specific effects or of general up-regulation of the lexical retrieval process (e.g.,

Holland et al., 2011). A related question is whether the activation of specific items prior to

stimulation is a necessary condition to observe tDCS effects. Resolving these questions may

shed light on the mechanisms of action of tDCS in various contexts. It is likely that tDCS

effects will interact with the network state at the point of stimulation, which could alter

performance during and/or for some time after stimulation.

The goal of our study was to gain a better understanding of the effects of tDCS on

word retrieval in healthy, young adults. Participants were asked to name sets of pictures and

their naming latencies at 'baseline' (pre-stimulation) were compared to their latencies during

stimulation as well as 15 minutes post-stimulation. The study was designed to 1) examine if potential effects would be item-specific vs. task general and 2) to directly compare the effects of tDCS at two cortical sites.

To address the question of item-specificity, we created three stimulus lists that were presented to all participants at different time points. List A items were named at all time points (before, during and after the stimulation period). List B items were named before and after stimulation but not during. Finally, list C items were named during stimulation only. This allows us to examine if potential effects of tDCS during stimulation would be specific to items pre-activated at baseline and if effects post stimulation would be specific to items produced during the prior stimulation period. On the other hand, if tDCS leads to a general up-regulation of lexical retrieval then we should see a comparable reduction of naming latencies across lists in the active condition relative to sham.

Our second goal was to directly contrast the effects of tDCS at two sites, the left IFG and left pSTG, chosen for their well-established role in lexical retrieval (e.g., Price, 2012) and salience as tDCS target sites in the treatment of stroke-induced aphasia (e.g., Crinion, 2016); In addition, positive tDCS effects have been reported at both sites in healthy young adults but have not been directly compared. In the present study we conducted the same experiment in two groups of participants, who received anodal and sham stimulation to either the left IFG or left pSTG. Comparable findings at both sites would lend support to the idea that tDCS can facilitate picture naming at multiple sites within the lexical retrieval network. On the other hand, the STG and IFG are thought to play different roles within this network, one common hypothesis being that temporal regions are involved in lexical storage while frontal sites would be more involved in the control of the relative activation of competing lexical candidates (Piai & Knight, 2018; Riès et al., 2015; Schnur et al., 2009).

3.3 Methods

3.3.1 Participants

Twenty-eight monolingual English speakers (Male = 13; M_{AGE} = 24.22, SD = 3.45), recruited from the student population at Bangor University took part in this study. Half of the participants were randomly assigned to the IFG condition and half to the pSTG condition. There were no significant differences between groups in terms of age or years of education (p > .14). All participants were right-handed, with no history of dyslexia or brain injury, and reported no contraindications for tDCS, as assessed by an in-house screening questionnaire. All data were collected between August 2014 and March 2015.

3.3.2 Ethical Considerations

All stimulation and experimental protocols were reviewed by the Bangor Brain Stimulation Committee, prior to approval from the School of Psychology's REC (2014-12525-A11682).

3.3.3 Stimuli

Stimuli were black and white line drawings (300 x 300 px) from a 416-item subset of the English (US) version of the International Picture Naming Project (IPNP); (Szekely et al., 2004) and Holland et al., (2011) have previously used subsets from this database in tDCS studies exploring picture naming in Italian and English, respectively.

We included items from the IPNP that had a lenient name agreement of 100%, i.e., accepting dominant names, synonyms, and morphophonological variants of the target. For example, both bike and bicycle are acceptable answers. Items with complex morphological structure were excluded (i.e., ice cream cone). We divided this subset into three 43-item lists matched on CELEX frequency (Baayen, Piepenbrock, & Gulikers, 1995) and on the Zipf frequency (1-7 scale) and contextual diversity (CD) values from the SUBTLEX-UK corpus

(van Heuven et al., 2014). Items with a higher lexical frequency or with a greater contextual

diversity are named more quickly (Adelman, Brown, & Quesada, 2006). On average, object

names were of a moderate frequency (see Table 3.1), and they ranged from low to high based

on both frequency counts [CELEX (natural logarithm) = min: 0.00; Max 6.08; SUBTLEX

(Zipf) = Min = 3.09; Max: 5.44].

Table 3.1.

Matching Statistics for Variables in each Target List (Means and SD).

	n	Complex Initial Phoneme (n)	Ln Celex Freq.[a]	Zipf Freq.[b]	CD[a]	Syllables[c]	Letters[c]	Phonemes[c]	RT	CDI AoA Categories % (n)	
A	43	11	3.37 (1.40)	4.41 (0.48)	0.093 (0.105)	1.33 (0.52)	4.72 (1.16)	3.84 (1.13)	713.5 (106.66)	8-16 months 17-30 months >30 months	46.5% (20) 14% (6) 39.5% (17)
B	43	11	3.03 (1.36)	4.32 (0.60)	0.089 (0.105)	1.42 (0.66)	4.79 (1.39)	3.95 (1.29)	703.06 (102.05)	8-16 months 17-30 months >30 months	46.5%(20) 14% (6) 39.5% (17)
C	43	11	3.20 (1.05)	4.36 (0.60)	0.076 (0.074)	1.44 (0.67)	5.00 (1.62)	4.16 (1.46)	718.5 (66.14)	8-16 months 17-30 months >30 months	44.2% (19) 14%(6) 41.9% (18)

Note: Freq. = Frequency; CD = Contextual Diversity; CDI = MacArthur Communicative Index; a = natural logarithm applied; b = Calculated using theZipf formula provided for SUBTLEX-UK (van Heuven et al., 2014); c = Kruskal-Wallis H calculated using mean ranks

A multivariate analysis of variance (MANOVA) with List (A, B, C) as an

independent factor conducted on CELEX frequency, Zipf frequency and on the log

transformation of CD was non-significant, Wilks' λ = .99, $F(6, 250)$ = 0.27, p = .95,

suggesting that the lists were well matched across all three variables. In addition, items from

each of the three CDI (Communicative Developmental Index; Fenson et al., 1994) age of

acquisition categories, included in the IPNP, were distributed evenly across lists, $\chi^2(4, N =$

$129) = .07$, $p = .99$. Kruskal-Wallis H tests showed no significant difference in mean ranks

for syllables [$H(2) = .43$, $p = .81$], letter length [$H(2) = .25$, $p = .88$] or phoneme length [$H(2)$

$= .87$, $p = .65$]. Finally, the three lists were matched on initial phoneme category (e.g., stop

consonants, fricatives) to minimise effects of articulatory planning time (Rastle & Davis,

2002). All matching statistics are presented in Table 3.1. A pilot study with 10 young adults

confirmed that the three sub-lists were well matched for difficulty as naming latencies were

equivalent across lists.

3.3.4 Picture Naming Task

Participants completed three picture naming tasks – Pre, During and Post stimulation

– in each of two sessions. Following a 10-item practice (non-overlapping with stimulus lists),

participants named pictures from two of the three 43-item lists (Pre: AB; During: AC, Post:

AB) for each naming task. A trial was made up of a 1000ms fixation cross followed by a

picture of a single object, which remained on screen until the participant's response triggered

the voice key. The experimenter coded response accuracy on a serial response box, which

triggered the next trial. The whole session was recorded. A 300ms beep sounded with the

onset of the picture to enable manual reference of response times at a later stage.

List A was presented at all three timepoints and the items in this set were subject to

repetition plus online stimulation. List B was presented pre- and post-stimulation only, and

List C during stimulation only. List B is subject to repetition priming post-stimulation but not

to direct stimulation. Items in List C were novel in relation to items in list A or B, and not

subject to repetition priming within a session. The BCB set allowed us to test for offline

tDCS effects on repeated B items and List C provided a direct test of item-specific versus

generalised effects of online tDCS. The items from both lists presented at any time point (Pre:

AB, During: AC, Post: AB) were intermixed and presented in a unique random order for

every instance of the task. All participant response times were manually recoded using Praat

(Boersma, 2006).

3.3.5 Transcranial Direct Current Stimulation

Transcranial direct current stimulation (tDCS) was delivered single-blind, using a

battery powered, constant-current stimulator (NeuroConn DC-Stimulator Plus, Rogue

Resolutions). Current was delivered through a pair of 35cm^2 conductive rubber electrodes, inserted into sponges moistened with 0.75% saline solution to improve conductivity and promote participant comfort (Dundas et al., 2007). Each participant received two sessions of tDCS (active or sham), separated by at least a week. For the IFG group, the anode was centred over FC5 which overlies the inferior frontal gyrus (which overlies the inferior frontal gyrus (e.g., Holland et al., 2011; Jurcak, Tsuzuki, & Dan, 2007; Koessler et al., 2009). For the STG group, the anode was centred over CP5 overlying the LSTG in accordance with a previous study (c.f., Sparing et al., 2008). In both groups the reference electrode was placed over the right supraorbital area. In active sessions, current was delivered at 1.5mA (Current Density = 0.043mA/cm^2) for a total of 20mins. Stimulation duration was informed by a general overview of the tDCS literature, which suggested a somewhat standard application of 20mins online stimulation. We chose 1.5mA as a trade-off between likelihood of observing a tDCS effect and participant comfort/blinding, in response to reports of ineffective blinding at higher intensities(N. J. Davis et al., 2013; O'Connell et al., 2012). In sham sessions, stimulation was ramped up, left on for 30s and ramped down. We employed a ramp-on/off of 15 seconds, in both stimulation sessions, in accordance with previous studies (e.g., Holland et al., 2011). Impedance was below 5kΩ before commencing stimulation in all participants. Figure 3.1 shows models of current density for both electrode montages created using the COMETS2 tool for MATLAB (Lee, Jung, Lee, & Im, 2017).

3.3.6 Procedure

Participants took part in two one-hour sessions, separated by at least seven days (M = 9.90, SD = 3.67). Sham or anodal stimulation was delivered in each session and the order of stimulation was counterbalanced across participants. At the beginning of the first session participants were given a brief overview of tDCS procedures, and an opportunity to ask questions, before completing the screening questionnaire and giving informed consent.
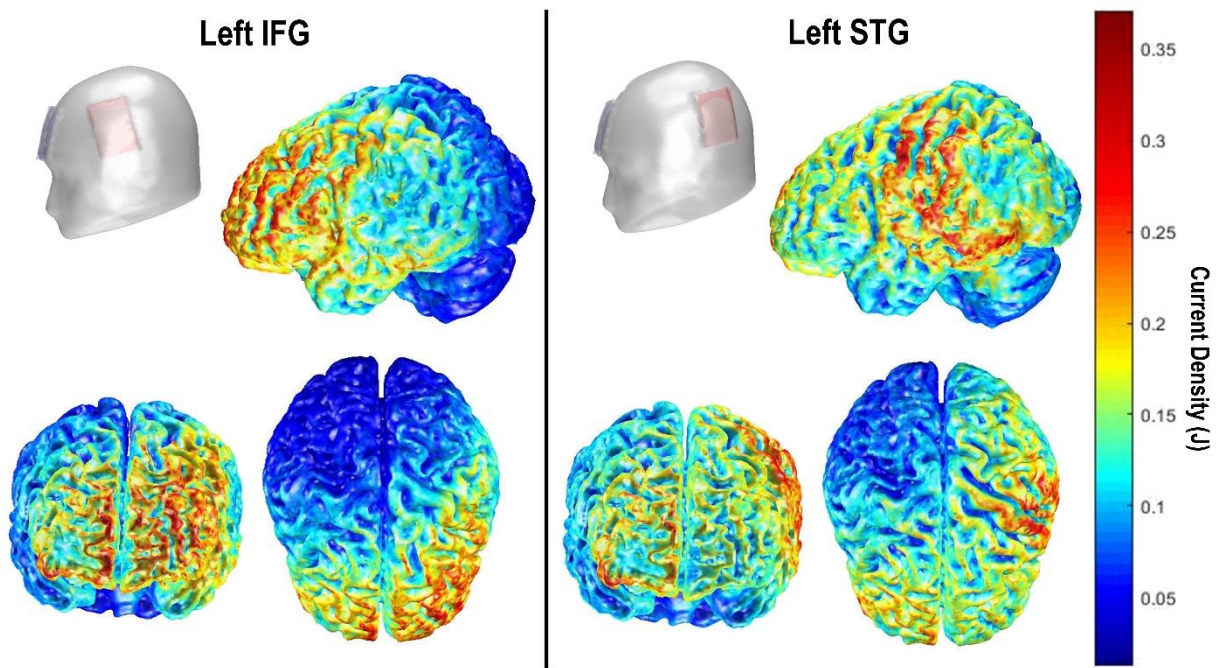
Figure 3.1. COMETS2 (Lee et al., 2017) current density (J) models for left IFG (left) and left STG montages (right).

The stimulator was switched on and the electrodes were placed on the scalp before the first naming task to encourage habituation, reduce impedance, and prevent distraction between tasks. Participants named 86 pictures before stimulation (AB), after 10 minutes of stimulation (AC), and around five minutes after the end of stimulation (AB). Approximately one minute into stimulation the sensations questionnaire was administered. At the end of the second session, we asked participants to indicate whether they thought they had received active or sham stimulation in either session before debriefing them. An overview of the procedure is presented in Figure 3.2.

3.3.7 Design

We employed a mixed design with Site (IFG, STG) as a between-subject factor and Stimulation (Sham, Active), Timepoint (Pre, During, Post), and List (AAA, BCB) as within-subject factors. The dependent variable in this study was onset naming latencies.
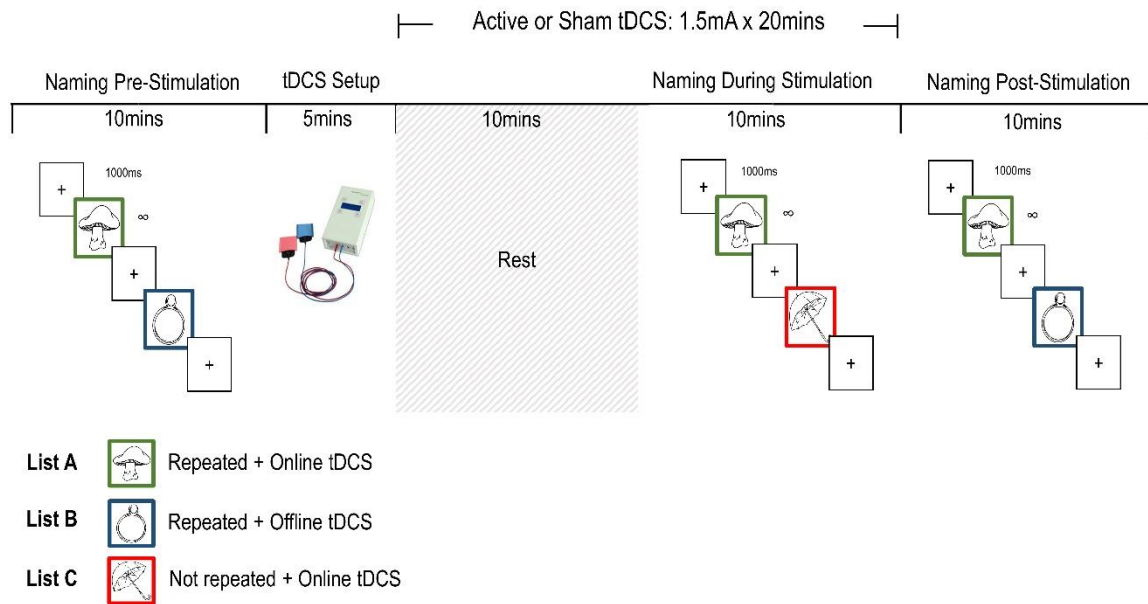
Figure 3.2. Single-session procedure outline.

3.3.8 Analysis

All analyses were conducted in Microsoft Open R 3.3.2 (Microsoft R Application

Network, 2014), a distribution of the R software (R Core Team, 2016), optimised for multi-

core processing.

3.3.8.1 Blinding and Sensations

We assessed blinding at the end of the study, by asking participants whether they

thought they had received active or sham stimulation in either session, asking them to guess if

unsure. Blinding was not intact as correct discrimination was significantly above chance (0.5)

for both groups [IFG: 78.57% (11/14), $\chi2(1) = 4.57$, p = .061; STG: 85.71% (12/14), $\chi2(1) =$

7.14, p = .011]. Overall, 82.14% (23/28) of participants could discriminate accurately

between Active and Sham sessions, $\chi2(1) = 11.57$, p = .001.

In addition, we measured the presence and intensity of after effects during stimulation

in each session, using a nine-item questionnaire, modelled on Brunoni et al. (2011) and

Poreisz, Boros, Antal and Paulus (2007). Participants indicated the incidence of a sensation

by choosing yes/no and then rated the intensity of sensations on a five-point scale (1 = Very

Mild, 5 = Very Strong).

All sensations were rated within the mild to moderate range. Table S1 (see OSF link)

provides intensity and incidence ratings for all sensations with accompanying radar plots for

visual comparison across sites. The intensity of Tingling, Heating and Pain was greater

during active stimulation compared to sham in the IFG group (all $p \leq$ .048), with a marginal

effect on Itching (p = .074). None of the comparisons between sham and active conditions for

the STG group were significant. Comparison of overall mean discomfort ratings between

groups was non-significant. Anecdotally, it is likely that differences in perceived *duration* of

sensations was responsible for suboptimal blinding in the present study, although the Poreisz

et al. (2007) questionnaire does not ask about such information.

3.3.8.2 Picture Naming Tasks.

Responses were coded as correct if the participant produced the dominant name, a

morphophonological variant, or a synonym of the dominant name. Incorrect responses, and

microphone errors (e.g., false trigger, failed trigger, external noise overriding the waveform)

that could not be reconciled from the recording, were excluded from analyses. Of the 14,448

data points included in our dataset, 1.70% (n = 245) of trials were lost to microphone errors,

with an additional 0.71% (n = 102) excluded as incorrect naming responses. As error rates

were less than 1% overall, we limited our analyses to response time data from correct trials

only. This left 14,101 (97%) data points for inclusion in the analysis.

3.3.8.3 Parsimonious Linear Mixed Effects Models

Parsimonious linear mixed effects models (LMMs) were conducted on inverse

reciprocal transformed RTs (InvRT = -1000/RTs, Baayen, Davidson, & Bates, 2008; Kliegl,

Masson, & Richter, 2010) with lme4 1.1-12 (Bates, Mächler, Bolker, & Walker, 2014) and

RePsychLing 0.0.4 packages (Baayen, Bates, Kliegl, & Vasishth, 2015) as outlined by Bates,

Kliegl, Vasishth and Baayen (2015; models with untransformed RTs produce similar results).

Models included centred, categorical fixed effects of Site (IFG, STG), Stimulation (Sham,

Active) and List[1] (AAA, BCB) as well as a centred, treatment-coded, categorical predictor of

Timepoint (Pre, During, Post), yielding two contrasts: Pre-During and Pre-Post. The two

contrasts allowed us to test for online and offline effects of tDCS, respectively. In the final

model, 321 trials (2.27%) were excluded as outliers (absolute standardised residual > 2.5),

and the model was refit to improve normality of residuals in accordance with a minimal a

priori data trimming approach (Baayen & Milin, 2010). The random effects in the final

parsimonious model included intercepts for both participants and items, within-item slopes of

Site and Timepoint, and within-participant slopes of Timepoint, Stimulation and their

interaction. Random effects correlations were included in the final model as they improved

the model fit. Beta weights and standard errors are presented alongside Wald approximated p-

values.

3.4 Results

Figure 3.3 displays the mean differences for the Timepoint contrasts, Pre-During, and

Pre-Post, split by List, Site and Stimulation. The full model summary from the final model is

presented in Table S2 of the supplemental materials (see OSF link). Table 3.2 includes mean

untransformed and inverse reciprocal transformed onset naming times (correct trials only)

and standard deviations for all conditions, after exclusion of outliers following model

criticism.

The final model revealed no significant main effects of List (AAA, BCB) or

Stimulation (Anodal, Sham), but there was a trend for naming latencies to be slower in the

STG group ($M = -1.55$ ($\sim$645ms)[2], $SE = 0.05$) compared to the IFG [$M = -1.63$ ($\sim$614ms)[2], SE

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[1] List was coded as a two-level variable (AAA, BCB) to facilitate easy application of contrasts between the two lists presented at each time point.
[2] Raw RT estimated on the basis of back-transformation of inverse reciprocal RTs (-1000/InvRT)

= 0.04; β = -0.10 $\pm$ 0.02, t = 1.76, p = .090]. As expected, naming latencies were shorter at

later time points compared to Pre, reflecting priming to repeated sets (Pre-During: β = -0.06

$\pm$ 0.02, t = -3.61, p < .001; Pre-Post: β = -0.12 $\pm$ 0.02, t = -6.65, p < .001). Also as expected,

there was an interaction between Time Point and List in the Pre- vs During comparisons (Pre-

Dur*List: β = 0.11 $\pm$ 0.03, t = 3.62, p < .001), as only the repeated set (list A) was subject to

priming. In contrast, the naming latencies for Set C (presented during stimulation only) were

comparable to the latencies obtained for set B pre-stimulation. In the pre-post contrasts, we

observed priming for both lists, but the reduction in naming latencies was larger for Set A

than for Set B (Pre-Post*List: β = 0.05 $\pm$ 0.02, t = 2.95, p = .004) reflecting the fact that at

post-test List A was being presented for the third time while list B was only presented for the

second time.

 Crucially, there was no evidence that active stimulation facilitated naming latencies in

relation to sham stimulation and this irrespective of stimulation site, as indicated by non-

significant higher-order interactions. As can be seen in Figure 3.3, naming latencies were

slower in the active condition in the IFG group for both List C (pre-during contrast) and List

B (pre-post contrast). No such effects were visible in the STG group nor for List A. There

was a marginally significant four-way interaction including the Pre-Post contrast

(Site*Stimulation*Pre-Post*List: β = -0.06 $\pm$ 0.04, t = -1.75, p = .081) but not the Pre-During

contrast, (Site*Stimulation*Pre-During*List: β = -0.05 $\pm$ 0.04, t = -1.36, p = .17).

Table 3.2.

Mean (standard deviation) untransformed (RT) and transformed (InvRT) correct onset

naming latencies for each of the conditions. Data were extracted from the final dataset

following model criticism to remove influential points.

		Sham			Active		
		Pre	During	Post	Pre	During	Post
RT							
IFG	A	661 (135)	612 (111)	610 (127)	658 (137)	612 (114)	606 (117)
	B	669 (168)		617 (129)	652 (158)		631 (140)
	C		654 (136)			669 (156)	
pSTG	A	717 (184)	661 (163)	641 (151)	699 (153)	648 (152)	637 (148)
	B	725 (231)		664 (172)	711 (194)		658 (162)
	C		715 (212)			706 (208)	
InvRT							
IFG	A	-1.56 (0.25)	-1.68 (0.24)	-1.69 (0.26)	-1.57 (0.26)	-1.68 (0.23)	-1.70 (0.24)
	B	-1.57 (0.28)		-1.68 (0.26)	-1.60 (0.29)		-1.65 (0.26)
	C		-1.58 (0.27)			-1.56 (0.27)	
pSTG	A	-1.47 (0.28)	-1.58 (0.25)	-1.63 (0.25)	-1.49 (0.26)	-1.61 (0.26)	-1.64 (0.25)
	B	-1.48 (0.31)		-1.58 (0.28)	-1.49 (-1.53)		-1.59 (0.26)
	C		-1.49 (0.28)			-1.51 (0.28)	

To follow up on the trend in the interaction, we conducted simple effects analyses by

fitting a separate LMM for the IFG group, for List B and C items only (see Table S3, OSF

link), which showed a disruptive influence of active tDCS on both List C (During) and List B

(Post) items (Stimulation*Pre-During$_{IFG}$: $\beta = 0.05 \pm 0.02$, $t = 2.58$, $p = .011$;

Stimulation*Pre-Post$_{IFG}$: $\beta = 0.06 \pm 0.03$, $t = 2.25$, $p = .038$).

We carried out additional analyses in order to rule out that our findings may have

stemmed from the action of confounded variables. The overall pattern of results remained

unchanged when we included either Blinding (Intact, Not-intact) or Stimulation Order (Sham

first or second) as categorical covariates into the final model, as well as when including word

frequency or participant baseline naming latencies as continuous covariates (see Table S2, OSF Link).
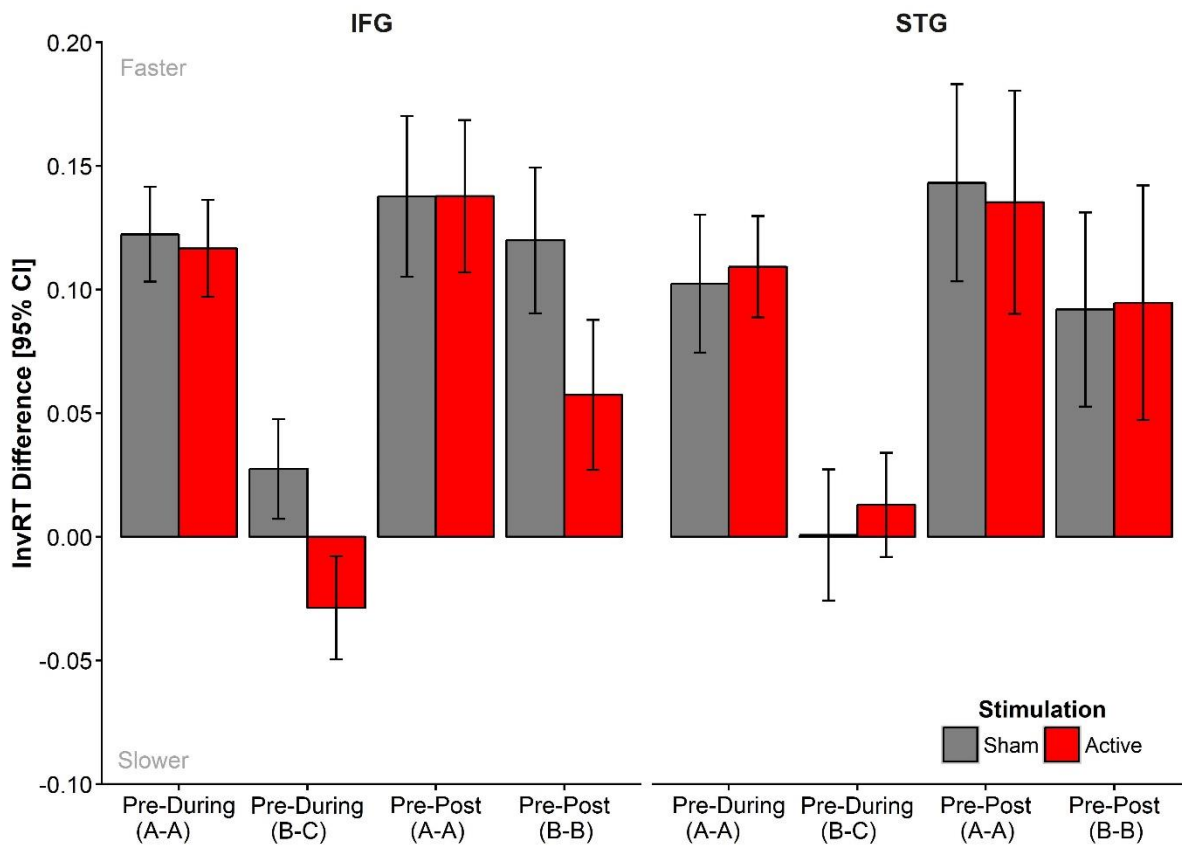
Figure 3.3. Mean difference in InvRTs for each of the Time Point contrasts, Pre-During and Pre-Post, entered into the model. Negative values reflect slower response times at the later time point. Data was generated based on fitted data extracted from final model and aggregated across participants. Means, adjusted for intra-subject variability, plus 95% CIs were extracted according to Morey (2008) and implemented with the summarySEwithin() function in R (Chang, n.d.)

3.5 Discussion

The aim of the present study was to clarify the conditions under which anodal tDCS applied to left hemisphere language sites may facilitate picture naming latencies in healthy adults. We built upon previous studies by directly testing for item-specific and generalised effects of tDCS through manipulation of item-familiarisation and through testing for both

online and offline effects of stimulation, in the same paradigm. In addition, we tested for the

robustness of these effects by comparing two left hemisphere sites critical for lexical

retrieval, the left IFG and pSTG. We also improved on earlier studies with careful matching

of key stimulus and participant characteristics, coupled with analyses that take variability

across both participants and stimuli into account.

In summary, our results provide a robust replication of the classical repetition priming

effect as naming latencies were reliably faster for previously named sets in all conditions.

However, active tDCS did not produce any additional facilitation. Given these null findings,

whether facilitation is best characterised as an item-specific or a generalised effect becomes a

moot point. We did observe an effect of active stimulation but it was a negative one: In the

IFG group, naming latencies were slower at post-test for set B items - those that were

presented at pre- and post-test, with the C set intervening during stimulation. This finding

was not predicted and should not be given too much weight. Direct investigation of this effect

or replication of the present study should be conducted. Tentatively, our results may suggest

that tDCS could interfere with retrieval when the lexical system has just been primed with a

different word list. It is interesting that this apparent interference effect of active tDCS is

limited to stimulation of the LIFG which has been linked to the modulation of patterns of

relative activation amongst competing lexical units (e.g., Hofmann & Jacobs, 2014; Meinzer

et al., 2016; Moss et al., 2005). There are several possible reasons why we did not observe a

facilitation effect of tDCS in our study. First, it could be argued that we might have observed

tDCS facilitation if we had used higher amplitude stimulation. We chose to deliver 1.5mA

tDCS as it would appear to be the highest intensity at which blinding can be preserved

(Ambrus et al., 2010, 2012; N. J. Davis et al., 2013; Kessler et al., 2012a; O'Connell et al.,

2012; Wallace et al., 2016). In their meta-analysis, Westwood and Romani (2017) reported

that current intensity, that varied between 1mA and 2mA in the studies included, did not

predict facilitation effects. Thus, it seems unlikely that our results are due to us using too weak an intensity of stimulation. Further step-wise evaluation of key methodological parameters within specific cognitive domains, such as titration of stimulation amplitude would be a useful development, as protocols from the motor domain do not necessarily translate to other cognitive domains (Marian E. Berryhill et al., 2014; Jacobson et al., 2012).

A potential problem is that even at a relatively low intensity (1.5mA) we could not achieve full blinding, with 85% of participants correctly discriminated between the two conditions when asked to guess at the end of the second session. This was surprising given that difference in stimulation intensity between sham and anodal conditions in this study was comparable to previous studies who claimed to have achieved successful blinding. This suggests that if using intensities greater than or equal to 1.5mA a between-subject design would be a more suitable option, as cross-over designs are likely to make differences in sensations more noticeable. On the other hand, a downside of between-subject designs is that differences between active and sham may be due to an insufficient control of participant characteristics across groups. Be this as it may, it is far from clear how participants' relative awareness of stimulation conditions may have affected performance in our study. One possibility is that it could have increased distractibility during stimulation. However, if this were the case one would expect to observe an increase in naming latencies during and possibly after active tDCS irrespective of stimulation location, in contrast to what we observed.

Thus, taking our results at face value, our study joins an increasing number of recent reports and meta-analyses that highlight the considerable heterogeneity of non-invasive brain stimulation effects on word production in healthy young adults (Klaus & Schutter, 2018; Westwood & Romani, 2017). One likely explanation is that, generally speaking, tDCS may not be effective when performance is already close to being optimal, as in healthy young

adults performing relatively easy tasks. In the present study (as in others), the stimuli were all familiar enough to be named with high accuracy in order to optimise the analyses of naming latencies. This may have left insufficient room for additional tDCS-driven facilitation in our groups of highly educated healthy young adults. From a stochastic resonance perspective, this would correspond to a low-noise, high-signal condition, leading to limited efficacy of tDCS (Fertonani & Miniussi, 2017). This ratio would have been reduced even further due to the repeated presentation of stimulus sets leading to strong priming effects. In such conditions, any effects would be small at best, and a much larger number of participants and items than typically used would be needed to reach sufficient power. This being said, a lack of power is unlikely to account for our results since there were no numerical trend for tDCS facilitation is any of our conditions. Consistent with this interpretation, tDCS effects in similar paradigms are much clearer in populations with sub-optimal levels of cortical excitability, such as in aphasia following brain damage (for reviews see Cappon et al., 2016; Crinion, 2016; Sandars, Cloutman, & Woollams, 2016) or in older participants affected by age-related decreases in neural plasticity (cf. Fertonani et al., 2014; Holland et al., 2011; Ross, McCoy, Wolk, Coslett, & Olson, 2011). Although we did not observe on-line facilitation for unprimed items (List C), our design did not allow us to examine if active stimulation of an unprimed list may lead to off-line improvement at post-test. This would have required presenting List C at post-test, as well as a new list to test for generalisation effects if tDCS enhances lexical retrieval more generally. Finally, electrode placement is a central factor that deserves further investigation as differences in electrode placement, however small, may have a significant impact on observed effects (Penolazzi, Pastore, & Mondini, 2013). Our electrode montage was chosen to maximally target the lexical processing network, but alternative montages may prove more effective. Furthermore, stimulation targeting other brain areas may well turn out to be a requirement for observing facilitation effects in young healthy adults. For example,

stimulation applied to DLPFC has produced some positive effects (Fertonani et al., 2010, 2014), although this probably reflects an improvement of broader task regulation processes rather than of lexical retrieval per se.

However, that is not to say that tDCS should be dismissed as a neuromodulatory device for the study of language processing in healthy adults. Tasks that avoid ceiling effects are perhaps better suited to probing questions about the healthy, young brain. For example, it has been argued that tDCS effects could be limited to studies using training paradigms (Mancuso et al., 2016). Along this line, substantial improvements during anodal tDCS in performance in healthy young adults have been reported in studies of vocabulary learning (De Vries et al., 2010; Fiori et al., 2011; Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008; Liuzzi et al., 2010; Meinzer, Obleser, Flaisch, Eulitz, & Rockstroh, 2007; Savill et al., 2015). Similarly, we recently observed improved performance in a foreign language vocabulary learning task with 1mA anodal tDCS applied over the left pSTG. Interestingly, this effect was only observed for participants with relatively lower (though normal) phonological memory abilities while active stimulation showed a tendency to impair performance in translation for participants with higher phonological memory abilities on the easier learning sets (Payne et al., 2017). In addition to their greater sensitivity, a major benefit of learning paradigms is that they are closer to those used with impaired populations, which may lead to further developments relevant to neurorehabilitation. Finally, investigations with potentially more effective electrical waveforms, such as transcranial random noise stimulation (tRNS) or transcranial alternating current stimulation (tACS) may prove fruitful for the modulation of higher order cognition in younger adults (e.g., Paulus, 2011; Penton, Dixon, Evans, & Banissy, 2017; Romanska, Rezlescu, Susilo, Duchaine, & Banissy, 2015; Snowball, Tachtsidis, & Popescu, 2013).

In conclusion, this study joins an increasing number of publications in casting doubts about the effectiveness of single session tDCS for improving word retrieval processes in healthy young adults. It remains possible that more reliable tDCS effects may emerge in picture naming and related tasks by administering multiple stimulation sessions, by tweaking stimulation parameters or by increasing sample size. However, this would also considerably increase the ratio of costs to potential benefits, suggesting that moving to more sensitive experimental paradigms, which include a training element could prove more promising.

Running head: STIMULUS DEVELOPMENT

Chapter 4: Development of Stimuli and Task Characteristics for an Associative Learning

Task

4.1 Introduction

The previous chapter and accompanying paper (Payne & Tainturier, 2018) demonstrated a null effect of tDCS on picture naming response times. Despite robust repetition priming effects, performance during and following application of anodal tDCS was not substantially different from performance under sham conditions. Contrary to our expectations, there was a trend for active tDCS to impair response times to previous unseen items, in participants who received stimulation of the left inferior frontal regions. One possibility is that well-practiced responses – may be less susceptible to effects of tDCS, particularly in healthy, coherent and established networks (Marian E. Berryhill et al., 2014; Miniussi et al., 2013). Under the stochastic resonance perspective proposed by Miniussi et al. (2013; Fertonani & Miniussi, 2017), network activation in well practice tasks, like picture naming of common objects, is likely to be highly coherent. The signal for a familiar object, presented as a prototypical representation of that object, will be strong and will cascade rapidly to the lexical level, with high signal-to-noise, such that successful retrieval is almost guaranteed. In this instance, weak electrical currents delivered with tDCS may have limited efficacy in perturbing/altering the network state in an observable manner, especially in healthy, young adults, following earlier repetition. One approach that has proven useful in examining the effects of tDCS, and that may mitigate risk of ceiling effects of this type, is the introduction of learning tasks.

Learning results in an adaptive change in network state that spans local and more distributed networks of activity. At first exposure to a new word, for example, the connections between the new word and its meaning will be weak or non-existent – a low coherence state, with low signal-to-noise. With repeated exposure, the associative connections are strengthened between co-occurring word form and meaning following Hebbian learning principles. As a result, the state of the network in response to a novel

stimulus begins to shift from a weak, low-coherence state, to one of more moderate coherence, over the course of the task. As tDCS alters resting membrane thresholds that that may promote LTP and LTD like processes, tDCS may optimally improve learning as it shifts from a low to a moderate coherence state, where the signal starts to outweigh the noise. Other factors at the participant and word levels will also alter the relative coherence of the response within the language network during a learning task. For example, participant's baseline phonological working memory ability impacts on their general success in learning novel words. At the word level, form similarity can be a highly salient cue to meaning that facilitates learning and retention of novel vocabulary.

4.2 Associative Learning Task

The present chapter describes the adaptation of an associative pseudoword learning paradigm first introduced by Breitenstein and Knecht (2002) and subsequently adopted by Flöel, Rösser, Michka, Knecht and Breitenstein (2008) in the first study to examine the effects of tDCS on associative word learning. In this task, learning is accomplished without feedback – target word-picture pairs appear 10 times more frequently than randomly paired foil trials of the same vocabulary targets. In a series of studies, Breitenstein and colleagues have demonstrated that this form of associative learning without feedback is as effective as learning with feedback (Breitenstein et al., 2004) and short but intensive exposure produces patterns of performance consistent with native language words (Breitenstein et al., 2007). Moreover, relative decreases in left fusiform and hippocampal activity, and complimentary increases in activity in left inferior parietal cortex, during learning, predicted vocabulary learning success and semantic knowledge for novel objects (Breitenstein et al., 2005). These effects demonstrate integration of multi-modal representations for novel pseudowords into the existing lexicon as measure by MEG, even after exposure periods as short as 20minutes (Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, & Zwitserlood, 2009; see also François,

Cunillera, Garcia, Laine, & Rodriguez-Fornells, 2017; Havas, Laine, & Rodríguez Fornells, 2017).

Flöel et al. (2008) reported that 1mA anodal tDCS applied to left superior temporal regions resulted in improvements in vocabulary acquisition and translation recognition performance, relative to sham or cathodal stimulation. A series of other studies, utilising similar stimulation protocols have reported improvement in learning and/or consolidation of novel pseudowords under anodal stimulation, although task protocols differed substantially between conditions (Fiori et al., 2011; Meinzer et al., 2014; Savill et al., 2015). All the tDCS studies published thus far have utilised pseudoword vocabularies, which may inform models of new word learning in the native language but eliminate the subtle differences between words in two languages. The use of pseudowords limits manipulation of key psycholinguistic factors very difficult, which act as proxies of a typical native speaker's knowledge about known words (e.g., frequency, familiarity, neighbourhood size) and their relationship to new words in another language (e.g., typological distance, phonological similarity).

In the two studies reported in Chapters 6 and 7, Dutch nouns were used as the target vocabulary that varied in phonological similarity to the English names for the object. Recently published multi-language picture naming norms (Duñabeitia et al., 2017) and databases of wordform similarity measures enable efficient and consistent selection of stimulus materials for cross-language research (Schepens, Dijkstra, & Grootjen, 2012; Schepens, Dijkstra, Grootjen, & van Heuven, 2013). We chose Dutch because of its close typological similarity to English and the large prevalence of high frequency phonological cognates.

In a pilot study without tDCS, we tested 10 healthy monolingual English speakers on their ability to learn 40 Dutch object names (20 cognates, 20 non cognates), utilising the same timing and display parameters as Flöel et al. (2008). In the original study, non-target foil pairs

were created by randomly pairing target words with incorrect pictures. We attempted this

with our 10 participants, but this resulted in a task where 75% of all trials included cognate

stimuli as words, picture or both, leading to a considerable bias in saying "non-match" to

phonologically dissimilar word-picture pairs and limited learning of non cognates. To reduce

the reliance on a similarity-based strategy and shift more of the focus to learning the

noncognate vocabulary, we needed to make cognates more difficult to identify.

In isolation, cognates are easier to identify and learn as foreign language learners

(FLLs) can make use of native language (NL) knowledge to support learning of form-

meaning connections (Ringbom, 2007). However, FL vocabulary items are rarely learned in

isolation, and target words are encountered with others, more or less similar in form, and

more or less relevant to the learning goals at that time. Learning of vocabulary items in a

foreign language is facilitated when the target words have dense phonological

neighbourhoods in the native language (Stamer & Vitevitch, 2012; Storkel et al., 2006) but in

the absence of semantics (as in early exposure to FL vocabulary) dense phonological

neighbourhoods produces an interference effect during spoken word recognition (e.g.,

Vitevitch & Luce, 2016). During initial exposure to FL stimuli, form-meaning connections

are weak, even for cognates, and are likely to be susceptible to phonological interference

effects.

To increase phonological interference for cognates and draw attention to noncognate

word-picture pairs, we created a phonological neighbourhood in Dutch for each of the target

words. Half of the distractors were phonologically related, and half were unrelated to target

words to ensure salience of phonologically dissimilar stimuli. In the face of a larger Dutch

neighbourhood Dutch-English cognates should be susceptible to interference effects from

phonologically related distractors disrupting the certainty with which form-meaning

connections are made to cognate translations. By removing direct comparisons between

cognate and noncognate pairs and presenting noncognates within equivalent Dutch neighbourhoods, the salience and relevance of noncognates will be enhanced. This should render noncognates more learnable. However, the tendency for new learners to equate form similarity to similar meaning, is unlikely to be eliminated and we would still expect to observe a cognate facilitation effect.

4.3 Stimulus Selection

A schematic overview of the stimulus selection process in presented in Figure 4.1. Object pictures were selected from the MultiPic database (Duñabeitia et al., 2017). The MultiPic database includes 750 drawings of common objects, normed on name agreement (H-Index, Shannon, 1949) and subjective visual complexity in seven European languages (British English, French, Spanish, Italian, German, Dutch (Netherlands), Dutch (Belgium)). We made use of the English and Netherlands Dutch databases for selection of target objects and nouns. Phonological similarity of translation pairs was based on the phonological normalised Levenshtein distance (PNLD) metric included in the Dutch-English translation database created by Schepens et al. (2013). PNLD is a measure of phonetic similarity at the whole word level and accounts for differences in phonetic features.

4.3.1 Phase 1: Target Extraction.

Using the MATCH programme (van Casteren & Davis, 2007) the best matching stimuli for two lists of 30 items ($n_{cognates} = 15$; $n_{noncognates} = 15$) were selected[3]. MATCH is designed to select the best matched subset of items based on the mean *and* standard deviation for each variable. One-hundred and sixty-two Dutch-English translation pairs, with entries in both the Multi-pic database and the Dutch-English database from Schepens et al. (2013),

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[3] Forty items were selected for the pilot study in the same manner, but in hindsight manipulation of vocabulary size and cognate status in relation to the original paradigm may add an additional level of difficulty in interpreting the results.

were extracted as the base dataset. Lists were matched on several factors that affect retrieval

of picture names and auditory word recognition in the native language. The lists were

matched on H-Index for name agreement and Visual Complexity (Multipic, Duñabeitia et al.,

2017); The Medical Research Council (MRC) subjective familiarity and English

phonological neighbourhood size (via N-Watch, Davis, 2005); the number of English and

Dutch phonemes (based on DISC++ phonological transcriptions; Schepens et al., 2013) and

lemmatised Zipf frequency for nouns and contextual diversity (SUBTLEX-UK; (van Heuven

et al., 2014). Cognate and non-cognate subsets were matched on PNLD (Schepens et al.)

between lists. Descriptive statistics are displayed in Table 4.1.

Table 4.1.

Descriptive Statistics for Matched Lists of Cognates and Noncognates.

Measure	List A		List B	
	Cognate	Noncognate	Cognate	Noncognate
H Index[a]	0.47 (0.47)	0.46 (0.53)	0.50 (0.47)	0.51 (0.51)
Visual Complexity[a]	2.56 (0.70)	2.48 (0.46)	2.45 (0.51)	2.80 (0.42)
MRC Familiarity[b]	558.47 (54.50)	568.33 (52.31)	571.47 (47.53)	548.67 (52.77)
Noun Zipf[c]	4.56 (0.56)	4.46 (0.47)	4.46 (0.57)	4.62 (0.52)
Contextual Diversity[c]	0.14 (0.14)	0.10 (0.07)	0.12 (0.15)	0.13 (0.15)
English Phonological NSize[b]	17.93 (9.41)	16.27 (7.81)	18.53 (7.57)	16.60 (7.38)
English Phonemes[d]	3.00 (0.38)	3.53 (0.74)	3.07 (0.46)	3.33 (0.82)
Dutch Phonemes[d]	3.40(0.74)	3.67 (0.82)	3.20 (0.41)	3.73 (0.80)
PNLD[d]	0.84 (0.05)	0.62 (0.07)	0.83 (0.04)	0.60 (0.07)

Note. a = Multipic Database (Duniabeitia et al., 2016); b = N-Watch (Davis, 2005); c = SUBTLEX-UK (van Heuven et al., 2014); d = Materials published in Schepens et al. (2013).

To confirm the suitability of the match, we conducted a MANOVA with List and

Cognate Status as between-item factors, and the nine psycholinguistic factors as dependent

variables. There was significant multivariate main effect of Cognate Status [Wilk's $\lambda = 0.17$, $F(9,48) = 26.82$, $p < .001$] but no significant main effect of List, or interaction between List and Cognate Status [Wilk's $\lambda = 0.97$, $F(9,48) = 0.18$, $p = .995$; Wilk's $\lambda = 0.86$, $F(9,48) = 0.86$, $p = .578$; respectively]. Univariate analyses revealed that the significant effect on Cognate Status was driven by expected differences in PNLD [$F(1,56) = 206.59$, $p < .001$], reflecting lower PNLD values for non cognates. In addition, there was a small but consistent effect of Cognate Status on the number of phonemes in both languages, with more phonemes in non cognates compared to cognates [English: $F(1,56) = 6.11$, $p < .017$; Dutch: $F(1,56) = 4.76$, $p < .033$]. However, this did not survive Bonferroni correction[4] and appeared to be a feature of the base dataset (Phonemes$_{Cognate}$: $M = 3.86$; $SD = 1.01$, Phonemes$_{Noncognate}$: $M = 4.02$; $SD = 1.07$, $p = .046$).

4.3.2 Phase 2: Creating Dutch Phonological Neighbourhoods

Sets of 12 phonological foils for each target item in Dutch (12*60, N = 720), for use as either phonologically similar or dissimilar auditory targets on foil trials, were created. Phonological foils had to conform to the following criteria:

- Phonological foils should be as similar to the Dutch target as possible, with emphasis on a matching/equivalent/similar onset (i.e., f or v; sj or sch).
- Should retain a syllable structure similar to the target
- Should be phonologically legal and pronounceable in Dutch (as assessed by a native Dutch speaker) to eliminate additional saliency of odd-sounding items.

As many possible phonological neighbours for each target word in Dutch were extracted from ClearPond (Marian, Bartolotti, Chabal & Shook, 2012), including cross-language

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[4] Bonferroni correction applied to univariate follow-up analyses for nine DVs: $\alpha_i = \alpha_{fw}/N_{tests} = .05/9$; $\alpha_i = .005$; Tabachnick, Fidell, & Ullman, 2019), p .270.

Dutch-English phonological neighbours for cognates. ClearPond did not yield enough

phonologically similar foils for every item so we used Wuggy (Keuleers & Brysbaert, 2010)

to extract additional Dutch words[5] and pseudowords with the same/similar onset and syllable

structure as target names. Duplicates were removed and validity of pseudowords as Dutch-

like was confirmed with the same Dutch-English speaker who recorded the stimuli. Full set

of foils is available on the OSF site for this chapter.

Phonetically unrelated foils (P-) were created by randomly pairing phonologically

similar foils for one target word (e.g., Target:/boek/ [BOOK] -> P+ Foil: /buik/) with other

targets phonetically unrelated to that foil (e.g., Target: /raam/ [WINDOW] -> P- Foil: /buik/).

To reduce the impact of any bias inherent in the selection process we split the available sets

of foils (12 P+, 12 P- per target) for each target into two sets and counterbalanced

combinations of phonologically similar and dissimilar subsets across stimulus lists A and B,

to produce four stimulus lists (A1, A2, B1, B2). For schematic depiction of this process see

Figure 4.1. Presentation of the lists was restricted such that participants learned List A1 or A2

on one day and List B1 or B2 on the other. The presentation of stimulus lists, and delivery of

stimulation, was counterbalanced across session order and participants, using a full 4 x 2 x 2

latin square design for each combination of list (A1, A2, B1, B2), stimulation type (Sham,

Active) and session order (Session 1, Session 2), leading to 16 possible presentation orders.

As a further control, block and trial orders were randomised across participants within each

learning task.

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[5] As far as our participants were concerned all the Dutch targets and foils are potential candidates so lexical status in Dutch was irrelevant for the task.
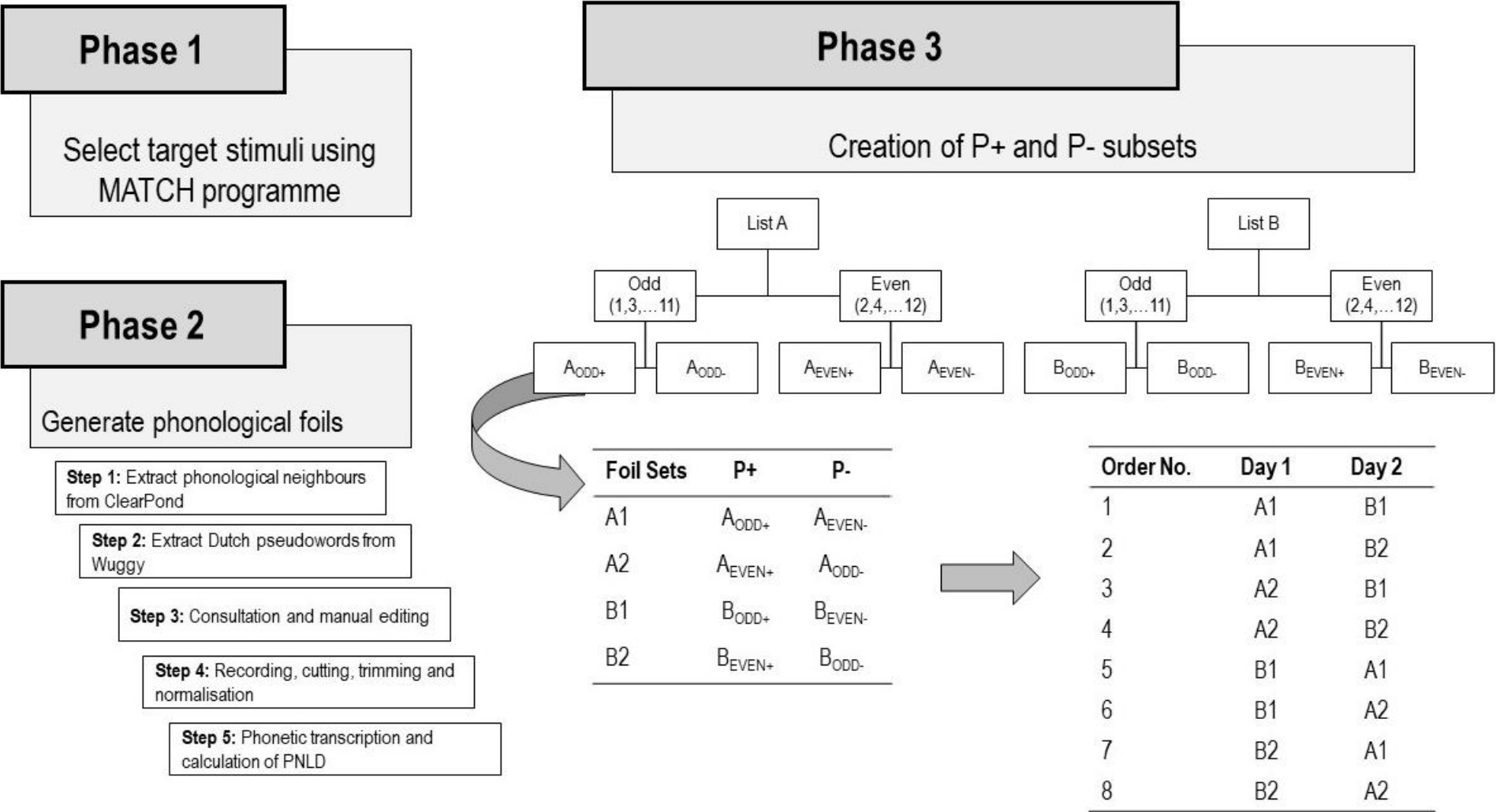
Figure 4.1. Graphical representation of the development process to create phonologically similar and dissimilar foils.

To calculate the PNLD of target-foil pairs, the phonological foils were phonetically transcribed into the DISC++ phonetic alphabet (Schepens et al., 2013). The original programme used to calculate the PNLD and apply the phonetic feature penalty was not available for use. Attempts to replicate this from information received from Schepens (personal communication) were unsuccessful. However, the correlation between raw PNLD (with phonetic feature penalties) and the values from the database for our stimulus set was $r =$ .80, in line with that reported in the original paper. We implemented the raw PNLD calculation in a custom R script to produce the phonological similarity values between foils and their Dutch and English target names. Figure 4.2 shows the distribution of raw PNLD values for cognate and noncognate targets in each sublist in reference to the Dutch and English transcriptions of object names. Distributions of phonological similarity measures are highly similar for all the foil-Dutch comparisons. The phonological similarity of foils to the English cognate names were higher than for foils to noncognate names, in line with our original intentions.

4.3.3 Phase 3: Phonologically Related and Unrelated Subsets.

To create phonologically similar and dissimilar subsets for foil trials, the phonological foils for each item were assigned a number from 1 – 12. The sets were split arbitrarily on even and odd numbers to form two subsets (herein called X and Y), within each list A and B. Each subset of foils, X and Y, were used to derive a further two subsets, i and j. Xi and Yi retain the pairings with the Dutch words from which they were originally derived, assigned as phonologically similar foils (P+) on incorrect trials. A custom script in R (R Core Team, 2014) was written to produce a random subset of phonologically dissimilar (P-) foils – subsets Xj and Yj. This script generates a dataframe of all pairings of Dutch picture names and derived phonological foils (5400 pairs per subset, with duplicates removed). Any pairs
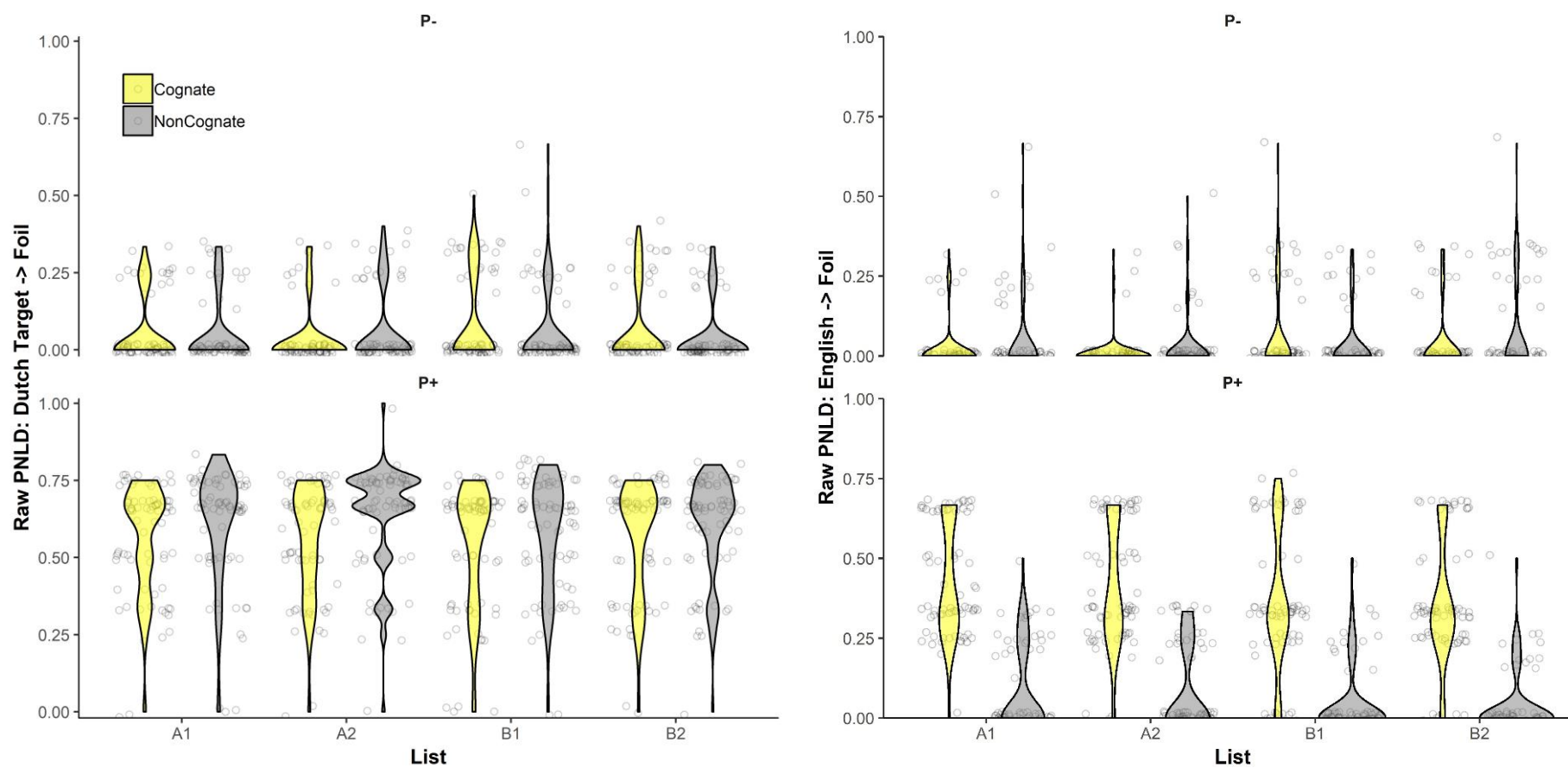
Figure 4.2. Raw PNLD values for comparison between Dutch targets and foils (A) and the same for comparison between English targets and

Foil (B) for cognate and noncognate stimuli in each sublist. Black diamond with error bars represents mean ± 95% bootstrap CI.

where the Dutch target and phonological foil began with the same letter were removed, to avoid additional sources of interference based on the saliency of the initial feature in form similarity identification (Hall, 2002; Hauer & Kondrak, 2011, p. 870). Six items were sampled for every Dutch target for use as P- foils, using the stratified() function from the devtools package (Wickham & Chang, 2016)..

On each presentation of the learning task (Day 1 and Day 2), participants were presented with stimuli from either List A or List B. For any given list both an X and Y subset must be presented, one of which included P+ foils (X_i or Y_i) and the other P- foils (X_j or Y_j). At the end of the foil selection process we were left with four independent testing lists – $A_{X_iY_j}$, $B_{X_iY_j}$, A_{Y_i,X_j} $B_{Y_iX_j}$ and four possible presentation orders across testing sessions (e.g., $A_{X_iY_j}$ then $B_{X_iY_j}$; $B_{Y_iX_j}$ then A_{Y_i,X_j}). To avoid any bias inherent in the sampling method all four possible presentation orders were counterbalanced, using a latin square, across participants and session.

Two correct and two incorrect Dutch words (one P+ and P-) were presented with every target picture, in each block. In all, participants encountered each correct word-picture pair a total of 10 times over the course of five blocks and each incorrect word-picture pair only once, maintaining the original 10:1 implicit learning ratio of Breitenstein & Knecht (2002). There were 600 trials per instance of the task: 300 correct trials, 150 P+ trials and 150 P- trials. See Table 4.2 for examples.

Table 4.2

Stimulus Type and Distribution Across Blocks in Each Instance of the Learning Task.

		Block 1	Block 2	Block 3	Block 4	Block 5	Total instance per item	Total trials per task (Item x 15)
Cognate book /bʊk/	Target	boek /bu:k/	boek /bu:k/	boek /bu:k/	boek /bu:k/	boek /bu:k/	10	150
	P+ Foil	bek /bɛk/	buik /bœyk/	buk /bʉk/	beuk /bø:k/	boeg /bu:x/	5	75
	P- Foil	stoet /stu:t/	joos /jo:s/	staar /sta:r/	jag /jag/	draaft /dra:ft/	5	75
						Total:	20/item	300/task
Noncognate window /ˈwɪndəʊ/	Target	raam /ram/	raam /ram/	raam /ram/	raam /ram/	raam /ram/	10	150
	P+ Foil	room /rom/	ruim /rœym/	roem /ru:m/	rijm /rɛim/	reem /re:m/	5	75
	P- Foil	nols /nɔls/	haus /haus/	Jaap /ja:p/	vaat /va:t/	kui /kœy/	5	75
						Total:	20/item	300/task

Note: Phonological transcriptions /xxxx/ presented in IPA transposed from DISC++ phonological transcriptions (Schepens et al., 2013); a = Each foil-picture pair appears in one block only.

To reduce the impact of any bias inherent in the selection process we split the available sets of foils (12 P+, 12 P- per target) for each target into two sets and counterbalanced combinations of P+ and P- subsets across stimulus lists, A and B to produced four stimulus lists (A1, A2, B1, B2). For schematic depiction of this process see Figure 4.3. Presentation of the lists was restricted such that participants learned List A1 or A2 on one day and List B1 or B2 on the other. The presentation of stimulus lists, and delivery of stimulation, was counterbalanced across session order and participants, using a full 4 x 2 x 2 latin square design for each combination of list (A1, A2, B1, B2), stimulation type (Sham, Active) and session order (Session 1, Session 2), leading to 16 possible presentation orders.

As a further control, block and trial orders were randomised across participants within each

learning task.
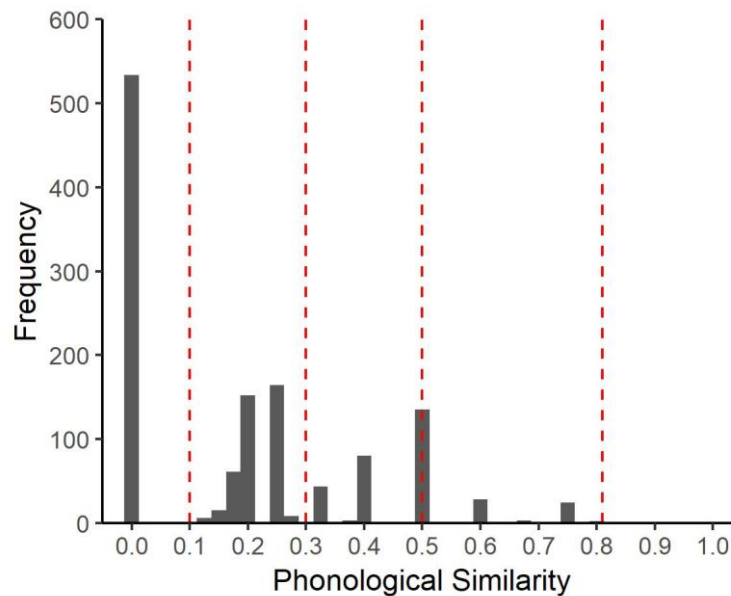
Figure 4.3. Histogram showing spread of phonological similarity between English names and

Dutch targets and foils.

4.3.4 Phonological Similarity

It was clear from the data presented in Figure 4.2 that there was some overlap in the

mid-range of phonological similarity values between phonological related and unrelated foils.

This is due to the loss of the phonetic feature penalty included in the original PNLD formula.

The difficulty lies in drawing a line between what should be considered phonologically

similar and what should. Similarity, the data are not truly continuous and when the data from

the foils is combined with the raw phonological similarity ratings of the targets then we see

that these values cluster into bands of phonological similarity ratings (Figure 4.3). To manage

this property of the data but retain the ordered nature of the values, a categorical, ordered

predictor with four levels was created based on the clustered values (Phonological Similarity

Band 1: [0, 0.1], Band 2, [0.11-0.30], Band 3: [0.31-0.50], Band 4: [0.51-0.8]).

4.3 Summary

In this chapter we described the stimulus development process for the vocabulary lists reported in Chapter 5 and 6. We carefully matched two lists of objects that varied in phonological similarity in relation to English object names and created a set of foils, carefully matched to sound Dutch-like, in order to moderate potential ceiling effects from cognates during learning.

Running head: NAME AGREEMENT

Chapter 5: Validating Name Agreement for Chosen Stimuli

5.1 Name Agreement Validation

A brief online picture study was created to assess name agreement for the selected pictures to ensure that participants' performance in learning and translation tasks would not be negatively affected by difficulty in identifying any of the pictures. Relevant data and analysis files can be found in the Chapter 5 folder on the OSF site.

5.2 Participants

Fifty-one participants completed the form through the participant panel at Bangor University, for one course credit. The recruitment pool was consistent with that intended for the learning studies. Data from six participants were excluded because they were not native speakers of English or Welsh. Responses from five participants were excluded because they indicated a history of a disorder that affected language processing (e.g., developmental dyslexia). One final participant was excluded because they produced 47% (28/60) "don't know" responses, where the maximum number of "don't know" responses was three for any other individual participant. Data were analysed from 39 participants ($M_{AGE} = 20.54$, $SD = 3.67$). Only three Welsh-English bilingual participants completed the form, but their data were retained as responses were not obviously different from English monolinguals.

5.3 Procedure

A single picture was presented on each page of the form with a short answer text box. Participants were asked to type in the name that best described the picture, in line with the original methods employed by (Duñabeitia et al., 2017). We did not collect visual complexity ratings. In addition, we asked participants to provide a rating of how difficult they found choosing a name for each object on a scale from 1 = Very Easy to 5 = Very hard.

5.3.1 Calculating Name Agreement

Data were processed according to the criteria outlined in Duñabeitia et al. (2017, *p.* XX). Several participants produced multiple alternative responses across different items, despite the instruction to only produce single word responses. We took the initial name within the cell as the response in this case. Spellings were corrected and 'Don't know' responses were excluded. Percent name agreement and Shannon's H-Index (Shannon, 1949) were calculated as a measures of name agree. The H-Index formula is reported below:

$$H = -\sum p_i \, lnp_i$$

where p_i is the proportion of trials where a response is provided, as a function of the total number of unique responses for a given target. This is multiplied by the natural logarithm of p_i. The values each alternative are summed for each target and multiplied by -1. Values of zero indicate a single, dominant response and increasing values indicated greater diversity in naming responses.

Overall, percent name agreement in the online sample was higher than in the original Multipic dataset (Payne$_{\%NA}$: $M = 92.50$, $SD = 13.00$; Multipic$_{\%NA}$: $M = 89.10$, $SD = 12.50$), owed to fewer alternative responses, as reflected in smaller overall H-index values (Payne$_{H\text{-}Index}$: $M = 0.30$, $SD = 0.41$; Multipic$_{H\text{-}Index}$: $M = 0.48$, $SD = 0.49$). Correlation for all data demonstrated moderate-strong positive relationships between datasets for both measures (Percent NA: $r(60) = .73$; H-Index: $r(60) = .71$) and very strong, negative relationships between percent name agreement and H-index within datasets (Payne: $r(60) = -.92$; MultiPic: $r(60) = -.96$).

5.3.2 Difficulty Ratings

Mean difficulty ratings were calculated for each word. Overall, participants found the words relatively easy to name ($M_{Difficulty} = 1.22$, $SD = 0.22$, Range = 1.00, 2.26). Difficulty ratings were correlated more strongly with the Multipic name agreement variables

(Mulipic%$_{NA}$: $\rho(60)$ = .52; Multipic$_{H\text{-}Index}$: $\rho(60)$ = -.51) than with the name agreement values

collected from the same sample (Payne%$_{NA}$: $\rho(60)$ = .33; Payne$_{H\text{-}Index}$: $\rho(60)$ = -.32). This

reflects the fact that the items with lowest name agreement were not necessarily the most

difficult to provide a name for subjectively.

5.4 Summary

Overall, the stimuli were named consistently by participants in the online sample and

showed strong similarity to the original norms. Difficulty ratings were relatively low but do

not necessarily reflect the true dominant names in participants. It is unlikely that there was

any confounding effect of name agreement in the learning studies.

Running head: BILINGUAL WORD LEARNING

Chapter 6: Investigating a Bilingual Advantage in Implicit Foreign Vocabulary Learning

6.1 Abstract

The goal of this study was to examine the contested claim that bilingualism may lead to an advantage in learning additional languages, over and beyond any advantages in phonological short term memory. In addition, we investigated the impact of the phonological relatedness between the known and the new language. These questions were addressed by comparing the learning trajectory and later recall of Dutch words in 28 highly proficient, early Welsh-English bilinguals and 35 English monolingual control participants. Over two consecutive days, the participants completed an implicit learning task in which Dutch words were paired with pictures of common objects. Learning was induced by varying the frequency of association between pictures and words in a 10:1 ratio for target words and matched foils. The phonological similarity between the Dutch words and their English translation equivalent was systematically varied for both targets and foils. To assess consolidation and retention, participants were asked to provide the English translation of each Dutch target immediately following the learning task, and again the next day and a week later. Phonological similarity acted a similarly strong cue to meaning for both groups during learning and translation. In the learning task, Welsh-English bilinguals did not show a learning advantage in terms of accuracy. However, they did show an advantage in decision times, becoming increasingly faster at accepting target vocabulary and rejecting distractors relative to monolinguals as learning took place. There was no bilingual advantage in translation accuracy. Crucially, the bilingual advantage in decision times was unrelated to phonological working memory abilities, although better phonological working memory was associated with better learning as previously reported. Finally, the bilingual advantage could not be explained by self-reported language switching frequency in everyday life. This study highlights the importance of using more sensitive measures in assessing foreign vocabulary learning. It also demonstrates that bilingual word learning advantages are not a mere artefact of variations on

phonological abilities. Future studies should investigate other potential explanations, such as enhanced perception and analysis of foreign phonological sequences, in combination with contextual and cognitive factors.

6.2 Introduction

Several studies have demonstrated a bilingual advantage in word learning on initial exposure to a foreign language. Day-to-day control of multiple languages and/or management of competing lexical forms is thought to enhance the word learning ability of bilinguals relative to their monolingual peers, although the specific source of such of an advantage is unclear. The present study aimed to test for a word learning advantage in a group of highly proficient, early bilinguals, in an exposure-based associative vocabulary learning task without feedback, that approximated immersion in an unknown language. Additionally, the use of an implicit, associative task allowed us to examine the evolution of learning as a function of exposure, and its subsequent impact on backward translation performance. When people encounter an unknown language, they naturally look for similarity between wordforms in known languages to aid learning and access to meaning. Although this general principle appears to hold for monolinguals and bilinguals, it is possible that bilingual experience might alter the sensitivity of the phonological system when encountering a foreign language, although the evidence is mixed in this regard (Antoniou et al., 2015; Burfin et al., 2014; Cenoz, 2003). One key factor that determines word learning success is the phonological similarity of novel words to known words (De Groot & Keijzer, 2000; Ecke & Hall, 2014; Ellis & Beaton, 1993b; Ringbom, 2007; Storkel et al., 2006; Vitevitch & Luce, 2016). A secondary aim of this study was to assess whether and how the learning process was moderated by bilingual experience in response to phonological similarity. As a final aim, we looked at two moderators attributed as potential explanations for the bilingual word learning advantage. Some studies have shown a bilingual advantage in phonological working memory which may underpin better word learning in this group (Papagno & Vallar, 1995; cf. Kaushanskaya, 2012; Ratiu & Azuma, 2015). Other studies have attributed a bilingual advantage in word learning to a possible advantage in cognitive

control, supposedly manifest through switching and control of multiple languages. We tested

for moderator effects of these two factors on learning and translation performance to better

understand the possible locus of any observed bilingual advantage.

On recognising an auditory signal as speech, we attempt to derive meaning from the

phonological sequences in the signal. All influential models of spoken word recognition

agree on the fundamental aspects of this process: 1) the acoustic signal and phonology of

incoming signal is processed pre-lexically 2) as the acoustic signal evolves, multiple possible

wordform representations stored in the lexicon will be activated in parallel; 3) the wordforms

activated will depend upon the similarity between the acoustic signal and prototypical

representations of known words stored in the lexicon; and 4) this process is competitive and

cascades to the semantic level, with the most highly activated representation winning out for

use (for review Weber & Scharenborg, 2012). One of the major sources of evidence in

support of interactive activation accounts comes from studies that examine the influence of

lexical processing on speech recognition. Known words from denser phonological

neighbourhoods are responded to more slowly and less accurately than words from sparser

neighbourhoods. Additionally, responses to known words with more high-frequency

neighbours are more impaired than for words with lower frequency targets (for review,

Vitevitch & Luce, 2016). Interestingly, the proposed mechanisms of speech recognition in the

case of multilingualism are language non-selective, and there is strong evidence that during

speech recognition, candidate wordforms from multiple languages are activated. For

example, in the visual world paradigm, when the non-task language of a distractor picture

name overlaps phonologically with the task language of a target picture, looking time to the

distractor is increased (e.g., Marian & Spivey, 2003; Weber & Cutler, 2004) in a similar

manner to phonological competitors presented to monolinguals (e.g., Allopenna, Magnuson,

& Tanenhaus, 1998). Phonological neighbourhood density impairs processing of target words

in native and L2 contexts but these effects are exacerbated in bilinguals relative to monolinguals because of activation of neighbours from both languages (e.g., Weber & Broersma, 2012) and further moderated by additional contextual factors, like age of acquisition, proficiency and dominance (e.g., Marian, Blumenfeld, & Boukrina, 2008).

Whilst larger cross-language neighbourhoods create more interference for multilingual speakers, they nevertheless benefit from whole-word phonological overlap and this factor acts as a pertinent source of lexical transfer between languages at all levels of bilingual proficiency (for discussion, van Hell & Tanner, 2012). Recognition of cognate (e.g., Dutch: /buk/ -> English / bʊk/ [BOOK]), translation pairs with highly similar wordforms and full conceptual overlap, is faster relative to noncognate translation equivalents (e.g., Dutch: /ra:m/ -> window). The cognate advantage is thought to arise from the combination of the bottom-up cascade of information at the phonological-lexical level from both languages and top-down reciprocal activation from the semantic level (e.g., Shook & Marian, 2013). What's more, the cascade of phonological activity can impair recognition, where meaning diverges in the face of phonological similarity (i.e., false friends) because multiple semantic representations are activated following cascaded activation of multiple phonological wordforms at the lexical level. Indeed, participants are slower to recognise false friends (e.g., Dutch: /brɑnt/ -> English: /faɪə/ [FIRE]) compared to cognates (Lemhöfer et al., 2004) and even noncognates in some cases (Dijkstra, Grainger, & van Heuven, 1999; cf. Haigh & Jared, 2007). Consistent with interactive activation accounts of speech perception, more recent computational models of bilingual speech perception propose an integrated lexicon for known words in multiple languages, whereby activation of targets and competitors within and between languages is achieved through winner takes all activation, accumulated over time as the speech signal evolves (Li & Farkas, 2002; Li & Zhao, 2014; Shook & Marian, 2013; Zhao & Li, 2010, 2013).

When naïve listeners encounter novel wordforms in any language, the novel stimulus engages the speech perception system in a manner similar to known words. However, the challenge for learners of new words is in mapping the novel wordforms to a semantic representation for future use. There is ample evidence that this can be achieved with a great deal of success, even with minimal exposure in both adults and children (Coutanche & Thompson-Schill, 2014; Yu & Smith, 2007). Founded in the cohort model of speech perception, the complementary learning systems account of word learning (CLS, Davis & Gaskell, 2009) proposes that on initial exposure, novel wordforms are constructed as episodic encounters to be retained for later use and updated through exposure. Furthermore, in order for a novel wordforms to become integrated in an individual's lexicon, the CLS account assumes that consolidation, through sleep is necessary. The evidence for this latter claim comes from studies that show that new words do not engage in lexical competition until after a period of sleep-based consolidation (Dumay & Gaskell, 2005, 2007; Tamminen et al., 2012, 2017; Tham et al., 2015). However, this process may be facilitated through the use of distributed learning episodes (Lindsay & Gaskell, 2013, 2009) or through fast mapping protocols that incorporate known referents (usually images) to facilitate semantic integration and stimulate lexical integration (Breitenstein et al., 2004, 2005; Coutanche & Thompson-Schill, 2014; Dobel, Junghöfer, et al., 2009). Originally proposed as a model of new word learning in a known language, and concurrent with the assumptions of speech perception models, the CLS model makes predictions that phonological form similarity between novel and known words should act as pertinent moderator of the learnability of novel wordforms (see Lindsay & Gaskell, 2010). In fact, several studies have manipulated phonological similarity at sub-lexical and whole wordform levels and have showed reliably that novel words more phonologically similar to words in a known language are learned more easily than words less phonologically similar (Bradley, King, & Hernandez, 2013; Carroll, 2012; De

Groot & Keijzer, 2000; Ellis & Beaton, 1993b; Kaushanskaya, 2012; Lotto & De Groot,

1998; Papagno & Vallar, 1992; Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010;

Service & Craik, 1993; Stamer & Vitevitch, 2012; Storkel, Armbrüster, & Hogan, 2006). In

contrast to studies that examine native language comprehension, novel words with dense

phonological neighbourhoods (Stamer & Vitevitch, 2012; Storkel et al., 2006) and similar

phonotactic regularities in the native language *facilitate* word learning (Bosma et al., 2017;

Ellis & Beaton, 1993b; C. Papagno & Vallar, 1992; Service & Craik, 1993). At the whole

word level, there is strong evidence that cognates are learned more quickly and more robustly

than noncognates (Bradley et al., 2013; Carroll, 2012; De Groot & Keijzer, 2000; Ellis &

Beaton, 1993a, 1993b; Lotto & De Groot, 1998; Raboyeau et al., 2010).

Storkel et al. (2006) proposed that even partial activation of known phonological

forms strengthens the representations of novel forms and links with semantic referents,

lending a greater advantage to consolidation of these novel forms compared with new words

with minimal overlap. Under the complementary systems (CLS) account, Lindsay and

Gaskell (2010) proposed that increased phonological lexical activation may facilitate fast

mapping and consolidation of novel wordforms. This is because more phonologically similar

vocabulary does not require the same effort in creating a representation for novel wordform,

as in the case of noncognate targets, but representation can be created through modification

of stored phonological representations. Over time these references are refined through

experience to create strong, independent wordform representations. Of interest to the present

study is the assumption under the CLS account that phonological similarity effects should

manifest themselves in a graded manner, rather than a binary one as implied in studies that

simply consider cognate and noncognate stimuli in siloed categories. Evidence of within and

cross-language neighbourhood effects supports such an idea.

The assumptions of the CLS account are consistent with the observation that even on initial exposure naïve listeners take phonological form similarity between any two (or more) languages as a cue to meaning (Ecke & Hall, 2014; Vanhove & Berthele, 2015). This so-called 'automatic cognate form assumption' appears to be utilised to a similar extent in monolingual and multilingual speakers. Ecke, Hall and colleagues (Ecke, 2015; Ecke & Hall, 2014; Hall et al., 2009; see also, del Pilar García Mayo & Alonso, 2015; González Alonso, 2012; Hall, 1992, 2002) have demonstrated that bilingual speakers learning L3 vocabulary in classroom settings make judgements about word meaning based on the perceived similarity between any and all combinations of languages, often utilising the language most similar to the target as the basis of the cognate assumption. However, factors like language status, dominance, age of acquisition, and mode of acquisition all influence the source language used for similarity judgements in a complex manner (see Ecke, 2015). Similarly, Nair et al. (2017) showed comparable effects of phonotactic regularity and neighbourhood size on novel word learning in monolingual and bilingual samples. Taken together, the above studies suggest that phonological form similarity is a robust facilitator in the acquisition of novel word forms.

Despite similarities in the mechanisms for speech comprehension and vocabulary acquisition, bilinguals show an advantage in acquiring and retaining L3 words relative to monolinguals acquiring the same vocabulary as an L2 (Bradley et al., 2013; Kaushanskaya, 2012; Kaushanskaya & Marian, 2009b, 2009a; Kaushanskaya & Rechtzigel, 2012; Kaushanskaya, Yoo, & Hecke, 2013; Nair, Biedermann, & Nickels, 2016, 2017; Papagno & Vallar, 1995; van Hell & Mahn, 1997). A bilingual advantage in word learning has been demonstrated using a variety of tasks. In a classic study using paired associate learning, Papagno and Vallar (1995) demonstrated an advantage in learning novel Russian words for bilingual versus Italian monolinguals but both groups performed similarly in learning lists of

familiar Italian words. Van Hell and Mahn (1997) examined novel vocabulary learning

performance in groups of participants with different levels of language learning experience.

Dutch speakers with around 6 years of English language instruction and at least two years in

French and German, learned Spanish vocabulary (Experiment 1), whilst English speaking

Americans with no or very little experience of foreign language instruction learned Dutch

vocabulary (Experiment 2). Van Hell and Mahn showed that participants who had more

language learning experience generally outperformed participants with less foreign language

experience. However, the experienced language learners had acquired their knowledge in

classroom contexts, and it is possible that experience of vocabulary learning strategies rather

than proficiency in a second language could explain the 'bilingual advantage' in these

studies.

In a series of studies, Kaushanskaya and colleagues have extended these findings and

have demonstrated a consistent bilingual advantage in word learning relative to monolinguals

(Bartolotti & Marian, 2012; Kaushanskaya, Yoo, & Van Hecke, 2013; Kaushanskaya, 2012;

Kaushanskaya & Marian, 2009b, 2009a; Kaushanskaya & Rechtzigel, 2012). For example,

Kaushanskaya and Marian (2009b) showed a general bilingual advantage for early English-

Mandarin, and early English-Spanish bilinguals, over monolinguals learning novel

pseudowords designed to be equally unfamiliar to all participants. Classroom experience

cannot explain the advantage observed here as both groups of bilinguals had acquired their

languages early on in a family context. Moreover, Kaushanskaya and Marian (2009a) showed

that English-Spanish bilinguals learned pseudowords more effectively than English

monolinguals and that bilinguals were less affected by interference from inconsistent letter-

to-phoneme mappings than were monolinguals. Similarly, Bartolotti and Marian (2012)

showed that bilinguals were less susceptible to competition from native-language competitors

in a recognition task, despite ensuring monolinguals and bilinguals achieved the same level of

performance during the learning phase. In other studies, employing explicit semantic

referents, in the form of pictures of common objects, bilinguals consistently outperformed

monolinguals. In Nair et al. (2016) both early and late Tamil-English bilinguals outperformed

monolingual speakers in learning novel Hindi vocabulary paired with familiar objects.

Moreover, the word learning advantage appears to be greater when words are paired with

concrete referents compared to more abstract referents (Kaushanskaya & Rechtzigel, 2012).

Although word learning in monolinguals and bilinguals appears to be affected to the same

extent by phonotactic regularity and neighbourhood size (Nair et al., 2017), some studies

have demonstrated a bilingual advantage only for phonologically dissimilar targets (Papagno

& Vallar, 1995), whilst others have reported an advantage that extends equally to

phonologically similar and dissimilar targets (Bradley et al., 2013; Kaushanskaya, 2012).

Despite the consistent finding of a bilingual advantage in word learning, the

mechanisms responsible for such an advantage are unclear. One substantial contributor to

word learning success is a participant's phonological working memory ability (Atkins &

Baddeley, 1998; Gathercole, 2006; Gathercole et al., 1999; Gathercole & Baddeley, 1993,

2014; Graves et al., 2008; Gupta, 2003; Gupta & Tisdale, 2009a; Majerus et al., 2008; C.

Papagno & Vallar, 1992; C Papagno & Vallar, 1995; Costanza Papagno et al., 1991; Vallar &

Baddeley, 1984). Better performance in tasks like nonword repetition and particularly

forward digit span (e.g., Marjerus et al., 2008) have been robustly associated with better word

learning performance and appears to be more strongly implicated in acquiring words that are

more phonologically distinct from words in known languages (Costanza Papagno et al.,

1991; Service & Kohonen, 1995). Some authors have claimed that phonological working

memory abilities may be stronger in bilinguals (Papagno & Vallar, 1995) but the evidence for

a general working memory advantage is inconsistent at best (Ratiu & Azuma, 2015). In

several studies, bilinguals outperformed monolinguals in word learning success despite

controlling for phonological working memory abilities between groups (Bartolotti et al., 2011; Bartolotti & Marian, 2012; Kaushanskaya, 2012; Nair et al., 2016, 2017). Although phonological working memory may support word learning in general (e.g., Gathercole et al., 2014), it is not clear that phonological working memory abilities underpin the bilingual advantage. We will attempt to clarify this issue in the current study.

Another potential factor that may contribute to a bilingual word learning advantage is based upon the abundance of literature that has proposed a bilingual advantage in cognitive control, that may result from having to control multiple languages, although the presence of such an advantage is hotly debated (Adesope et al., 2010; Bialystok et al., 2012; Costa et al., 2009; de Bruin et al., 2015; Hilchey & Klein, 2011; Paap & Greenberg, 2013). Bartolotti and Marian (2012) trained bilingual and monolingual groups up to the same criterion on a novel vocabulary and tested for the influence of lexical competition in eye and mouse tracking measures. In their study, monolinguals looked for longer at native-language distractor pictures than bilinguals, which suggested greater influence of competitors for monolinguals. However, mouse-tracking results showed increased activation of both targets and distractors when a competitor was present on the screen in mouse trajectories towards distractors than bilinguals. Taken together, the authors suggested that despite increased activation to targets and distractors, bilinguals were able to more effectively manage competition from a known language (see also, Kaushanskaya & Marian, 2009a). Bartolotti and Marian attributed this finding to an assumed bilingual advantage, despite the contentious nature of such effects (e.g., de Bruin, Treccani, & Della Sala, 2015), and despite not actively testing for such an advantage in their study. Moreover, Bartolotti, Marian, Schroeder and Shook (2011) suggested that bilingual experience and inhibitory control may have independent contributory effects on language learning. However, it is unclear if this was really the case, as the two factors were not contrasted in the same analysis. More recently, Verreyt, Woumans,

Vandelanotte, Szmalec and Duyck (2016) showed that balanced switching bilinguals outperformed both balanced and unbalanced non-switching bilinguals in two cognitive control tasks, suggesting that the degree of language switching may be the putative mechanism underpinning a cognitive control advantage. Consequently, these findings present the question of whether varying levels of inhibitory control amongst a bilingual sample differentially contribute to language learning ability within this group, to provide an explanation for potential processing differences. In sum, both phonological working memory and cognitive control, manifest from management of multiple languages, may contribute to a potential bilingual advantage in word learning.

One feature common to all the studies outlined in the previous section is the use of explicit learning tasks. On the one hand, explicit learning tasks are efficient as learning can be accomplished with feedback and recognition can be reached with relatively few trials. Control over precisely what is learned avoids crystallisation of incorrect pairs but often these studies employ only a small number of stimuli, limiting the ability of the researcher to manipulate psycholinguistic variables in a meaningful way. Generally. people are not introduced to new words in an explicit manner but instead infer meaning from referents that co-occur in the environment. Most previous studies have exclusively looked at word learning rather than the role of mapping phonology to explicit representations of a participant's semantic knowledge (i.e., pictures of familiar objects). This approach is called fast mapping and supports the rapid integration of new wordforms into the existing lexicon. In a series of studies, Breitenstein and colleagues (Breitenstein et al., 2005; Breitenstein, Kamping, Jansen, Schomacher, & Knecht, 2004; Breitenstein et al., 2007; Breitenstein & Knecht, 2002; Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, & Zwitserlood, 2009) have demonstrated successful learning of novel pseudowords without feedback in an associative learning paradigm, in monolingual participants. Learning in this task is accomplished through

repeated exposure to novel spoken wordforms paired consistently or inconsistently with pictures of common objects as concrete semantic referents. Retrieval performance following the associative learning task is similar to explicit learning (Breitenstein et al., 2004) and target wordforms begin to engage in lexical competition, and show activation profiles in MEG similar to known words, after just 20 minutes of exposure (Dobel, Junghöfer, et al., 2009; see also, Havas, Laine, & Rodríguez Fornells, 2017), even for words that include non-native phonemes (Dobel, Lagemann, et al., 2009). In this paradigm, the distributed nature of exposure to consistent pairings over five blocks of trials reflects a fast mapping approach that may underpin the rapid development of lexical integration in this paradigm, that is otherwise is at odds with the assumptions of the CLS account regarding the role of consolidation. Furthermore, behaviours exhibited in an associative paradigm arguably provide a more naturalistic approximation of the inferencing process that occurs as a function of exposure in novel learners. The automatic nature of the task removes the influence of any potential strategies employed during explicit tasks, as exposure to the stimuli is rapid and time-limited, relying on speech comprehension and associative learning mechanisms, common to monolinguals and bilinguals. Moreover, this paradigm allows a more fine-grained analysis of the learning process as it evolves in both groups, potentially providing subtle insights into the learning process.

In the present study we adapted the Breitenstein paradigm to include real foreign language vocabulary targets because of the advantages described above. In that case, if a bilingual advantage was observed then it can be attributed to language experience rather than because of a differential response strategy. Studies previously conducted by Breitenstein and colleagues and most studies examining a bilingual advantage in word learning have utilised pseudowords. Although pseudowords present an opportunity to reliably control specific aspects of the stimulus, they do not include subtle cues that natural language targets do, and

learning may be overestimated. Moreover, psycholinguistic variables cannot be readily

manipulated, which is vital in examining how existing knowledge impacts new word

learning. In the present study, Dutch was chosen as the target language because it is

typologically close to English, with a high volume of phonologically similar translations, that

are sufficiently high in frequency to include picturable common objects (Schepens et al.,

2013). Moreover, both English and Dutch are typologically distant to Welsh, and exposure to

Dutch is likely to produce limited co-activation of Welsh wordform representations, ensuring

as common a learning experience as possible for Welsh-English bilinguals and English

monolinguals. In turn, this would increase sensitivity in detecting a bilingual advantage

during learning and/or in backward translation. Dutch targets were selected based on a

gradient of phonological similarity with English words (Schepens et al., 2013), and these

targets were then consistently paired with pictures of common objects. Therefore, this

paradigm represents a departure from previous studies of cognate status that dichotomised

stimuli into two strict categories and allowed for the examination of degrees of phonological

similarity and their effects on learning of novel words, and any potential interactions with

bilingual experience. To reduce ceiling effects to the most phonologically similar targets,

foils with both high and low phonological similarity were included, to capitalise on

phonological interference effects that arise from dense neighbourhoods for known words.

This would hopefully encourage participants to notice 'noncognates'. The foils also provide

an alternative source of information about the learning process, namely how our two groups

of participants used phonological information to accept or reject potential candidate words

over the course of the task, a critical skill that indexes real learning rather than recognition

alone.

    In summary, the aim of the present study was to extend previous findings of a

bilingual advantage in foreign word learning, observed largely in explicit studies, by

examining a potential learning advantage in an implicit associative learning task. We expected that bilingual participants would outperform monolinguals in learning new words as measured in the progress across blocks in the implicit learning task. In addition, we expected to observe a bilingual advantage in explicit recall and maintenance of the new vocabulary following consolidation. This was assessed in three backward translation attempts that were administered immediately following training, the day after and at a one week follow-up.

In addition, the fact that we probed performance in the learning task at 5 time points meant that we could pinpoint any potential differences in response to targets or foils as a much subtler potential index of a bilingual word learning advantage. Furthermore, we manipulated phonological similarity between Dutch words to be learned and their English translation equivalents in order to gain a better understanding of the mechanisms that may underlie a bilingual advantage in foreign vocabulary learning. As we have seen, prior studies have provided conflicting results in this respect and it is thus unclear which specific predictions should be made. Finally, we tested for potential moderating effects of phonological working memory abilities and everyday language switching frequency, a proxy for inhibitory control, as both factors have been implicated in previous studies examining a bilingual advantage in word learning.

6.3 Method

6.3.1 Participants

Seventy-nine participants were recruited from the student population at Bangor University and the surrounding area. Sixteen participants were excluded and replaced for the following reasons: technical error (n = 3), history of dyslexia (n = 1), hearing impairment (n = 1), failure to follow instructions properly (n = 2), disruption of testing timeline (e.g., weather disruption, failed to turn up to main testing sessions; n = 6), or because they were not a native speaker of English and/or Welsh (*n* = 3). Of the remaining 63 participants, 35 were monolingual speakers of English, and 28 were Welsh-English bilinguals (Table 6.1 for demographic information). The bilingual participants were all fluent bilinguals, all learning both languages by the age of eight, with the majority learning both languages before the age of four.

Table 6.1.

Demographic and background information for Monolingual and Bilingual participants.

Values are means and standard deviations in parentheses.

	Monolingual (n = 35)	Bilingual (n = 28)
Age	20.03 (1.85)	21.54 (4.59)
Nonword Repetition Scaled Score[a]	11.17 (2.18)	10.68 (2.37)
Digit Span Scaled Score[a]	8.97 (2.31)	8.46 (2.19)
Phonological Memory Subscale Score[a]	99.06 (18.79)	98.21 (11.00)
BPVS-III Scaled Score[b]	109.57 (7.59)	101.89 (11.54)**
English Proficiency[c]	9.93 (0.28)	9.46 (0.80)***
Welsh Proficiency[c]	-	9.31 (1.45)
English Age of Acquisition (years)	-	2.53 (2.38)
Welsh Age of Acquisition (years)	-	1.00 (1.32)
BSWQ: Overall Switching[d]	-	18.05 (2.79)
BSWQ: Switch to English[d]	-	9.46 (2.36)
BSWQ: Switch to Welsh[d]	-	8.50 (1.93)
BSWQ: Contextual Switching[d]	-	8.96 (2.15)
BSWQ: Unintended Switching[d]	-	6.50 (2.30)

a = Comprehensive Test of Phonological Processing 2; b = British Picture Vocabulary Scale-III; c = Self-reported proficiency on a scale from Beginner 1-10 Native/Native-like averaged across speaking, understanding, reading and writing; d = Bilingual Switching Questionnaire; ** *p* < .01; *** *p* < .001

6.3.2 Background Measures

Background information is presented in Table 6.1. We administered an in-house

questionnaire that recorded demographic information, language background, proficiency in a

foreign language, and knowledge of Dutch before the study (0 = none, 9 = native/native-like).

Participants completed the phonological memory subtests (Nonword Repetition and Memory

for Digits) from the Comprehensive Test of Phonological Processing – Second Edition

(CTOPP-2; Wagner, Torgesen, Rashotte & Pearson, 2013), and the British Picture

Vocabulary Test – III (BPVS-III; Dunn, Dunn, Styles & Sewell, 2009). The basal set for the

BPVS for all participants was set 10 (age 14+) and the test was administered according to

published testing procedures, with the exception that words were pre-recorded for

administration via E-Prime 2.0. The raw and scaled scores were calculated for each

participant in all tasks. Wilcoxon rank-sum tests showed that both groups of participants were

matched on age and CTOPP-2 phonological memory composite scaled scores (W_{AGE} =

567.50, p = .28; $W_{PMEMORY}$ = 410.50, p = .27). Bilingual participants rated themselves as

equally proficient in both of their languages (Wilcoxon signed-ranks, V = 93, p = .95).

Bilinguals rated themselves as highly proficient in English overall but less so to monolinguals

(W = 284, p < .001). Additionally, bilinguals achieved lower scaled scores on the BPVS-III

(W = 282.50, p = .004). Bilingual participants also completed a version of the Bilingual

Switching Questionnaire (BSWQ; (Rodriguez-Fornells et al., 2012), adapted for Welsh-

English speakers. The BSWQ is a self-report measure of switching behaviours and includes

four subscales: Switch to English, Switch to Welsh, Contextual Switching, and Unintended

Switching, with a maximum score of 15 for each subscale. An overall switching score is

calculated by summing the scores from the Switch to English and Switch to Welsh subscales.

In Soveri, Rodriguez-Fornells and Laine (2011) higher overall switching totals predicted

smaller mixing costs in proficient bilinguals. The BSWQ has not be validated in Welsh-

English bilinguals but reliability of the data provided by Welsh-English bilinguals for the whole scale was good (McDonald's ω = .743). We did not have enough data to examine subscale reliability or to conduct factor analysis to confirm the structure of the questionnaire.

Figure 6.1. General procedure outline.

Day 1		Day 2		Day 3		Follow-up
Consent & Screening Form	24 HOURS	Translation 1 (Day After)	24 HOURS	Translation 2 (Day After)	ONE WEEK	Translation 1 (Follow-up) / Translation 2 (Follow-up)
Learning Task 1		Learning Task 2		Background Tests & Demographics		Debrief
Translation 1 (Immediate)		Translation 2 (Immediate)				
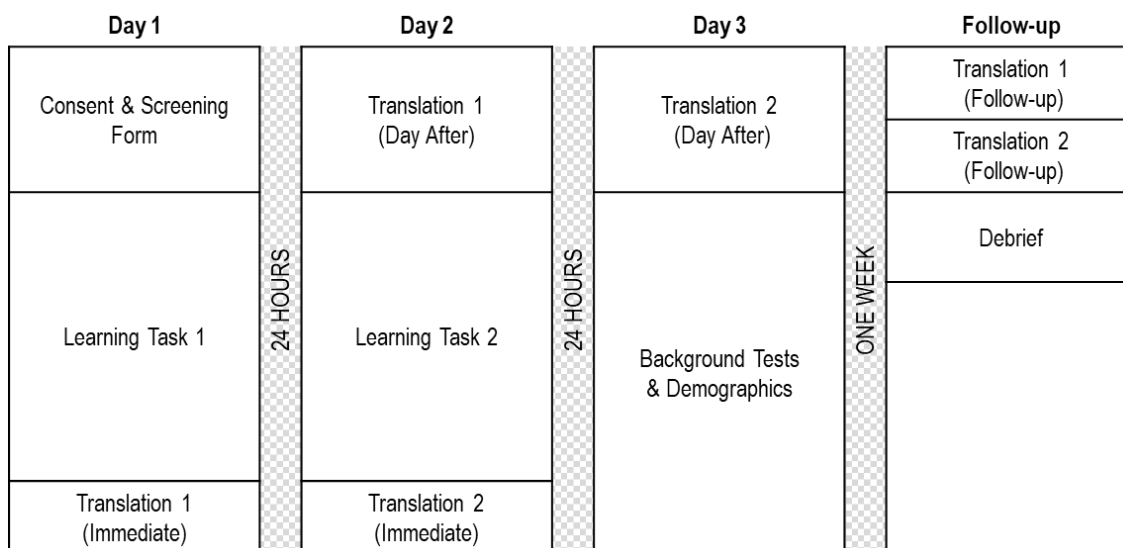
6.3.3 General Procedure

Participants took part in four experimental sessions (see Figure 6.1 for diagrammatic overview). Sessions one to three were completed on consecutive days (approx. 60mins each) and the fourth, follow-up session a week later (15mins). In the first session, participants were given detailed information about the experimental sessions before giving informed consent. Participants then completed the first learning task, immediately followed by the first backward translation task. At the beginning of day two, participants completed a translation task for the second time, associated with the stimulus list they had learned on day one. On the same day, they then learned the remaining vocabulary list and a backward translation task for that list. In the third session, participants completed the second translation task for the list learned the day before, followed by the background tests and demographic questionnaire. Participants returned to the lab one week after the third session and completed the translation tasks for List A and B before being debriefed. List order was fully counterbalanced across participants and session.

6.3.4 Stimuli

Target and foil stimuli described in Chapter 4 were used in this study. A MANOVA was conducted with List as a between-item factor with the nine psycholinguistic variables used for matching as dependent variables. This analysis revealed a non-significant multivariate main effect of list, Wilk's $\lambda = 0.97$, $F(9, 50) = 0.15$, $p = 0.998$, demonstrating good matching properties between the lists as a whole. See Table 6.2 for descriptive statistics.

Table 6.2.

Means (Standard Deviation) for Psycholinguistic Variables for Both Stimulus Lists.

	List A		List B	
	Mean (*SD*)	*Range* (min, max)	*Mean* (*SD*)	*Range* (min, max)
H Index[a]	0.47 (0.49)	0, 1.58	0.50 (0.48)	0, 1.55
Visual Complexity[a]	2.52 (0.58)	1.68, 3.59	2.63 (0.49)	1.40, 3.70
MRC Familiarity[b]	563.40 (52.73)	447, 643	560.07 (50.69)	462, 645
Noun Zipf[c]	4.51 (0.51)	3.49, 5.73	4.54 (0.54)	3.59, 5.84
Contextual Diversity[c]	0.12 (0.11)	0.01, 0.55	0.13 (0.14)	0.02, 0.60
English Phonological NSize[b]	17.10 (8.54)	3, 34	17.57 (7.41)	1, 30
N English Phonemes[d]	3.27 (0.64)	2, 5	3.20 (0.66)	2, 6
N Dutch Phonemes[d]	3.53 (0.78)	2, 6	3.47 (0.68)	3, 5
PNLD[d]	0.73 (0.13)	0.50, 0.90	0.71 (0.13)	0.50, 0.88

Note. a = Multipic Database (Duniabeitia et al., 2017); b = N-Watch (Davis, 2005); c = SUBTLEX-UK (van Heuven et al., 2014); d = Materials published in Schepens et al. (2013).

6.3.5 Vocabulary Learning Task

The associative learning task was adapted from the paradigm reported by Flöel et al. (2008) and programmed in E-Prime 2.0 (see Figure 6.2a). The aim of this task was for participants to acquire an association between a concept – a colour picture of a known object – and the phonological form of the 30 Dutch words in a stimulus set. Learning in this task is accomplished without feedback through statistical exposure to consistent and inconsistent pairings between Dutch targets and foils, and the corresponding pictures. Consistent pairings between object pictures and the to be learned target in Dutch are presented 10 times over the course of the task, twice per block, for five blocks. Different foils were presented with each

picture on inconsistent trials in every block, creating a 10:1 Target:Foil ratio. A block

consisted of 120 trials, made up of 60 target-picture pairs (2 x each target pair) and 60 foil-

picture pairs (30 x phonetically similar, 30 x phonetically dissimilar), for a total of 600 trials

per task instance. A trial consisted of a Dutch target word presented via desktop speakers,

followed by a picture presented 200ms after onset of the word. The picture stayed on the

screen for 1000ms and participants were instructed to "intuitively decide if the word and

object match", whilst the picture was on the screen. Participants decided whether a word-

picture pair was a "match" or "non-match" via a button press with two fingers on their right

hand. Participants were told that only responses given within a 1000ms time window would

be included in the data analysis. Participants saw a "Time Exceeded!" notice if they

responded after 1000ms. The inter-trial interval was limited to 1000ms, where a blank screen

appeared following the participants' response (1000ms) or time exceeded warning (800ms +

200ms blank screen). Response buttons were counterbalanced across participants but

remained consistent across both learning sessions. In line with a signal detection theory

approach we focused on discrimination performance, whether a correct match (hit) or

incorrect match response (false alarm) was made on target and foil trials. We also extracted

response latencies from the onset of the picture on each trial.

6.3.6 Translation Task

We assessed retention/consolidation of Dutch vocabulary learning with a productive

backward translation task from Dutch to English (see Figure 6.2b). On each trial, a fixation

cross was presented for 750ms in the centre of the screen, followed by the auditory

presentation of a Dutch target name. A question mark appeared simultaneously with the onset

of the Dutch word to prompt translation into spoken English. Responses were self-paced by

the participants. Trials moved on once accuracy had been coded using a serial response box

by the experimenter. Each trial consisted of a single block of 60 trials, made up of two

presentations of each target name in Dutch presented in a random order for each instance of

the task. Translation tasks were recorded for offline reference and recoding due to technical

inconsistencies with the voice key component of the serial response box. The primary

outcome was translation accuracy (correct, incorrect) but response latencies were extracted

manually with Praat (Boersma & Weenink, 2018), taking the latency from the onset of the

Dutch target to onset of the participants' translation response in English. Response accuracy

was coded using both strict and more lenient criteria. Strict criteria limited correct responses

to the exact name of the English object picture. More lenient criteria allowed synonyms for

the object picture.
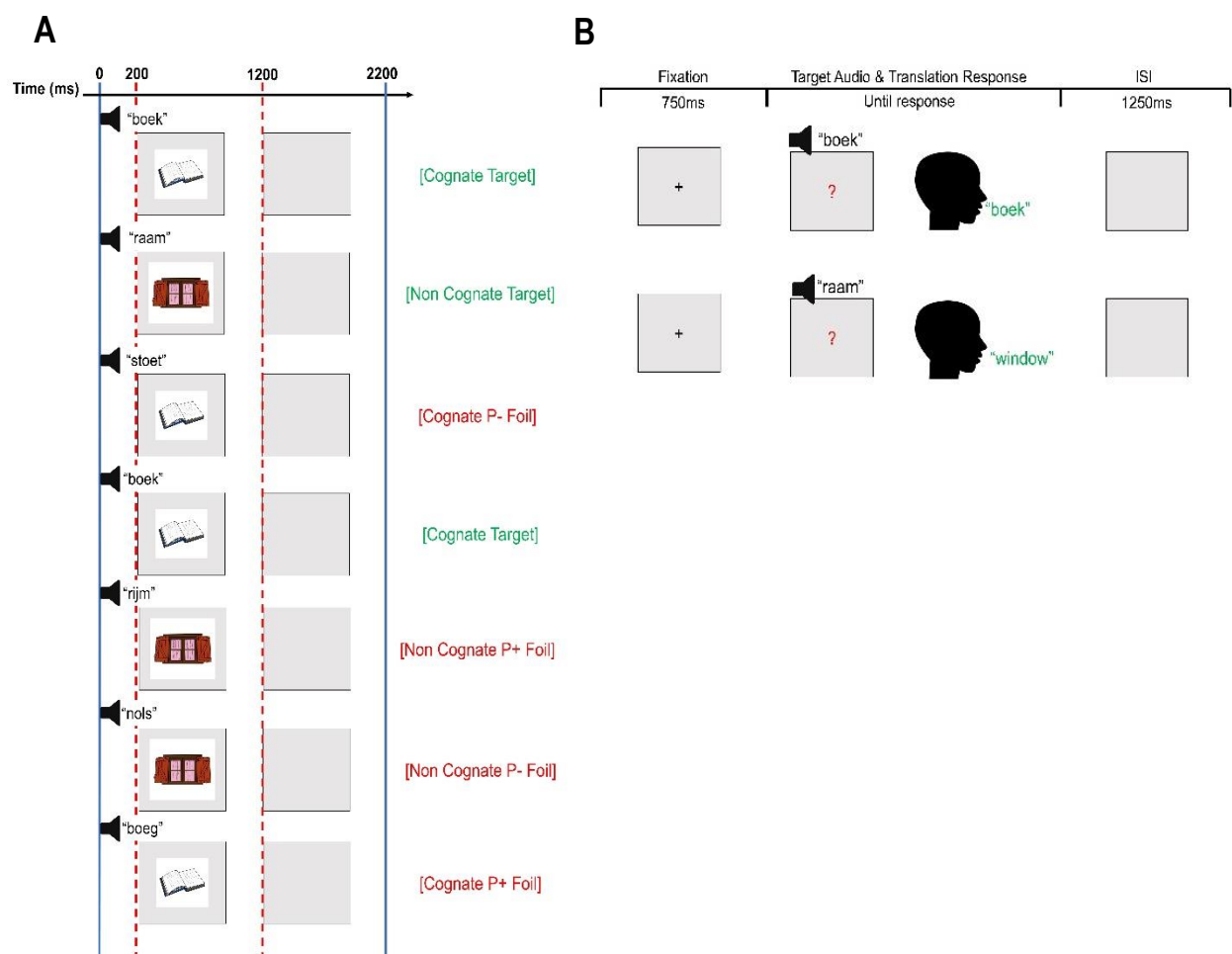
Figure 6.2. Example trials and structure for the learning task (A) and translation task (B).

6.3.7 Design and Data Analysis

This study employed a mixed between-within subjects design. Two dependent variables were collected and analysed for the learning task: non-match/match responses (0 = non-match, 1 = match) and response latencies of the response, collected from the onset of the object picture.

Previous studies examining learning in similar tasks have focused purely on hits – correctly identified 'match' responses – which potentially conflates accurate responding with a biased response strategy. On each trial, participants had to make a two-forced choice decision between a match and non-match response and therefore true learning should be characterised by a response strategy that not only maximises hits on target, match trials, but also minimises false alarms on non-match, foil trials. In line with a signal detection approach we consider discrimination performance, or rather the relative difference in the proportion of hits and false alarms to be indicative of learning. Moreover, previous studies utilising a paradigm such as this have dismissed response latency data as purely a marker of arousal rather than indicative of a learning response. Under a signal detection framework, response latencies may provide subtler insight into the nature of the learning process, when other moderators are present. In analyses of response latencies, we included data for hits and correct rejections, as the parallel to discrimination performance. Evidence of greater learning would be observed if response latencies decreased to both hits and correct rejections as exposure increased. Response latencies to false alarms are not appropriate as responses on these trials reflect an error in responding, rather than affirmation of learning.

To properly examine the effect of phonological similarity for foils and targets, it was necessary to calculate the PNLD between the Dutch target and foil stimuli with the English name of the picture they were paired with. We were unable to apply the phonetic feature penalty described by Schepens et al. (2013) to the transcription of the Dutch foils and as such

we could only include the raw phonological normalised Levenshtein distance (Raw PNLD) in our analyses. The Raw PNLD values for the original 60 targets were correlated with their penalised PNLD values at $r = .80$. Without the feature penalty Raw PNLD values were clustered into four distinct bands, leading to the creation of a categorical, ordered predictor with four levels (Phonological Similarity Band 1: [0, 0.1], Band 2, [0.1-0.3], Band 3: [0.3-0.5], Band 4: [0.5-0.8]). In parsimonious mixed effects models fit to the learning task data then, a between-subjects fixed effect of Language Status (Monolingual, Bilingual) and within-subjects fixed effects of Trial Type (Target, Foil), Block (1-5) and Raw PNLD Band were included. Moderating effects of other key fixed factors provide insight into how over blocks and as function language status and phonological similarity.

In the translation task, accuracy of the translation response was recorded (0 = incorrect, 1 = correct). Fixed effects of Stimulation Type (Sham, Active), Session (Immediate, Day After, Follow-up) and Raw PNLD Bands (Band 1 – Band 4) were included as within-subject fixed effects.

6.3.7.1 Parsimonious Mixed Effects Models.

All analyses were conducted in Microsoft Open R 3.3.2 (Microsoft R Application Network, 2014), a distribution of the R software (R Core Team, 2016), optimised for multi-core processing. For implementation of mixed models under a signal detection framework see the work of Wright and colleagues (Jacobs et al., 2016; Schwartz & Wright, 2012; Wright et al., 2009, 2011; Wright & London, 2009). Parsimonious mixed effects models were conducted with the lme4 1.1-12 (Bates et al., 2014) and RePsychLing 0.0.4 packages (H. Baayen et al., 2015), as outlined by Bates, Kliegl, Vasishth and Baayen (2015; see also Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). Generalised linear mixed models (GLMM) with a logit link function were fit to the discrimination responses from the learning task (Non-match = 0, Match = 1; see Wright & London, 2009, for similar application of

GLMMs), and the accuracy data from the translation task, whilst linear mixed models (LMM) were fit to response latencies to hits on Target trials and correct rejections on Foil trials. The two-level fixed effects of Stimulation (Sham, Active) and Trial Type (Foil, Target) were centred and sum-coded (e.g., ~+0.5, ~-0.5; see Nieuwenhuis, te Grotenhuis, & Pelzer, 2017). In the learning task, the natural logarithm of Block was entered as a continuous linear predictor, removing the need for a quadratic term in the model. For the translation task, centred backward difference contrasts were applied to the fixed effect of Session (Immediate, Day After, Follow-up), resulting in two contrasts: Immediate vs. Day After; Day After vs. Follow-up. backward difference contrasts to compare performance for items as a function of increasing similarity, comparing one phonological similarity bin with the previous (i.e., Band 1 vs. 2; 2 vs. 3; 3 vs. 4). All main effects and interaction terms were included in the fixed effects component of the models.

Residual plots were tested for uniformity with the DHARMa package (Hartig, 2016) for GLMMs and LMERConvenienceFunctions package for LMMs (Tremblay & Ransijn, 2015). We took a minimal *a priori* data trimming approach following Baayen and Milin (2010), reducing any heteroskedasticity with appropriate transformation before excluding influential trials from LMMs using the romr.fnc function from the LMERConvenienceFunctions package. Wald approximate p-values are presented for GLMMs. The Satterthwaite degrees of freedom adjustment was applied to generate approximate p-values for LMMs, using the lmerTest package (Kuznetsova et al., 2016). All data presented in figures were extracted from mixed effects models using the effects package (Fox, 2003; Fox & Hong, 2009) and figures were created using ggplot2 (Wickham, 2016).

6.4 Results

6.4.1 Associative Learning

Of the 75,000 trials in the learning dataset, 2,569 (3.43%) trials were excluded because participants timed-out and 106 (0.14%) were removed because response latencies were less than 300ms, based on visual examination of raw distributions (remaining: 72,325, 96.43%). In the GLMM for the learning data, the parsimonious crossed random effects structure included intercepts for participants and concepts, with slopes of Block, Raw PNLD quartiles, and Trial Type within participants, and slopes of Language Status and Block within concepts. The residuals in the final model conformed to a uniform distribution ($p = .32$). The complete model formula for the final parsimonious model is presented below:

glmer(Discrimination ~ LanguageStatus*log(Block)*Phonological Similarity*TrialType +

(1 + log(Block) + Phonological Similarity + TrialType | Participant) +

(1 + LanguageStatus + log(Block) | Concept),…

The response time data were restricted to correct match responses to targets and correct rejections to foils, for a total of 50,241 trials. In the LMM fit to untransformed response latencies, the residuals were heteroskedastic. Following the steps outlined in Kliegl, Masson and Richter (2010), a Box-Cox power transformation produced a lambda of ~0.56, suggesting that either the natural logarithm or square root transformations were most appropriate. The log transformed data provided the best goodness of fit to a theoretical normal distribution[6] (Cramer von-Mises $T_{\text{Untransformed}} = 22.32$; $T_{\text{SquareRoot}} = 6.66$; $T_{log} = 1.20$; fitdistrplus, Delignette-Muller & Dutang, 2015). Model estimates and figures reported for log-transformed data. The parsimonious random effects structure for the LMM fit to response latencies was identical to the discrimination GLMM. Random effects correlations improved

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[6] Cramer von-Mises T is one of five Goodness of fit indices provided in the fitdistrplus package for comparison against a theoretical distribution. Lower values of T indicate better fit

model fit of the LMM a little (AIC_{DIFF} = 31.90). Inspection of residuals at this stage showed some slight heteroskedasticity. The romr.fnc (Tremblay & Ransijn, 2015) automatically identified 775 trials (1.54%, trim = 2.5) as influential points from the log-transformed model and removal substantially improved model fit (AIC_{DIFF} = 5879.61). The final parsimonious model is presented below:

lmer(log(RT) ~ LanguageStatus*log(Block)*RawPNLD*TrialType +

(1 + log(Block) + RawPNLD + TrialType | Participant) +

(1 + LanguageStatus + log(Block) | Concept),…

6.4.1.1 Model Outcomes. Figure 6.3 shows the discrimination data and Table 6.3 includes the model estimates from the parsimonious GLMM. Estimates extracted from the parsimonious model for the response latency model showed highly similar response patterns in Phonological Similarity Bands 1 and 2, and in Bands 3 and 4. For simpler interpretation of model estimates we combined the response latency data for stimuli in Bands 1 and 2, and Band 3 and 4, into Low similarity and High similarity categories, respectively. For brevity this reduced model is presented below in Figure 6.4 and Table 6.4 but summary figures and model estimates for the initial model can be found in Appendix A. Only significant effects are discussed below.

6.4.1.2 Discrimination. The proportion of Match responses was greatest to targets than to foils overall (Trial Type) and the proportion of match responses increased from Block 1 to Block 5 [log(Block)]. Increasing phonological similarity between Dutch stimuli and English object names biased participants to make more match responses overall, particularly to target stimuli (Phonological Similarity; Phonological Similarity:Trial Type). The repetition of consistent word-picture pairs across blocks resulted in pronounced learning effects for stimuli in all phonological similarity bands. Overall, this was characterised by a progressive

increase in hits to targets, with a concurrent decrease in false alarms to foils

[log(Block):TrialType]. The size of this learning effect was not significantly moderated by

phonological similarity but note the relative floor effect for foils in the lower phonological

similarity bands and relative ceiling effect to targets in the highest band that may have

masked potential effects. Contrary to the predictions of this study, the pattern of responses

for monolinguals and bilinguals was similar and Language Status did not moderate any of the

effects described above. In other words, bilingual participants did not show a bilingual

advantage in associative learning accuracy.
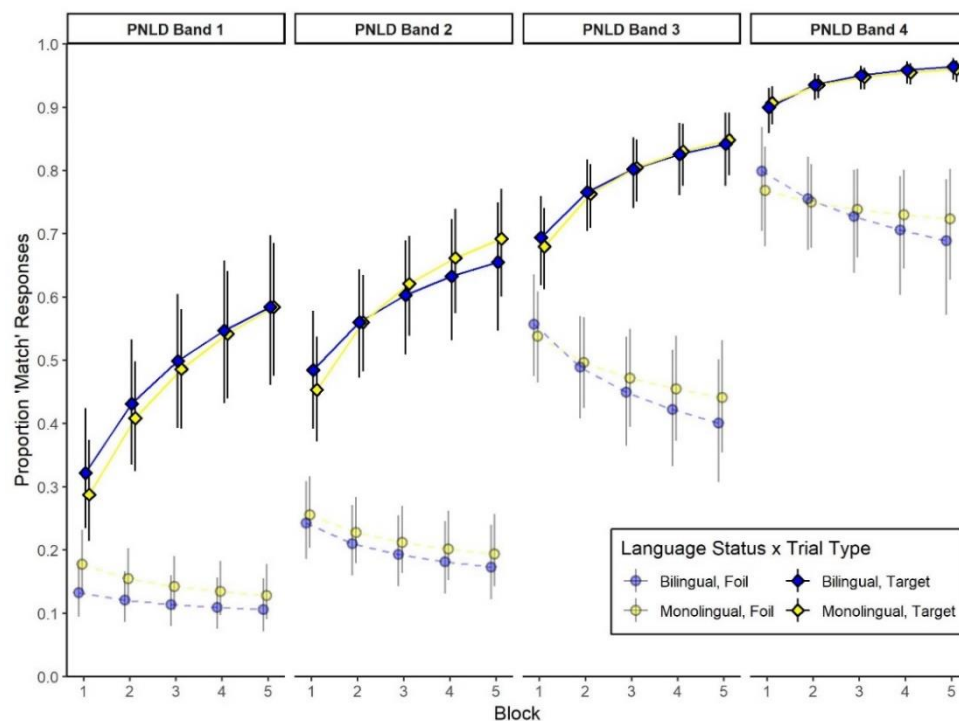
Figure 6.3. Proportion 'Match' responses (hits vs. false alarms) with 95% CIs as a function of

Trial Type, Block and Language Status, panelled by Phonological Similarity bands.

Table 6.3.

Model Estimates from the Parsimonious GLMM for Discrimination Performance

	lnOR	SE	z	p
(Intercept)	-0.273	0.13	-2.21	**.030**
Language Status [Monolingual, Bilingual]	-0.008	0.16	-0.01	.959
log(Block)	0.180	0.05	2.71	**<.001**
Phonological Similarity				
Band 1 vs. Band 2 (PSim1)	0.651	0.07	9.39	**<.001**
Band 2 vs. Band 3 (PSim2)	1.107	0.07	16.19	**<.001**
Band 3 vs. Band 4 (PSim3)	1.290	0.10	13.08	**<.001**
Trial Type [Foil, Target]	0.840	0.10	10.16	**<.001**
Language Status:log(Block)	0.081	0.07	0.55	.273
Language Status:Phonological Similarity				
Language Status:PSim1	-0.125	0.12	-0.96	.303
Languag3 Status:PSim2	-0.047	0.12	-0.36	.700
Language Status:PSim3	0.015	0.19	0.12	.936
Language Status:Trial Type	-0.204	0.20	-1.20	.318
log(Block):Phonological Similarity				
log(Block):PSim1	-0.122	0.05	-2.18	**.020**
log(Block):PSim2	-0.027	0.05	-0.34	.600
log(Block):PSim3	0.041	0.08	0.68	.618
log(Block):Trial Type	0.840	0.04	17.36	**<.001**
Trial Type:Phonological Similarity				
Trial Type:PSim1	0.126	0.11	1.08	.246
Trial Type:PSim2	-0.367	0.11	-3.49	**.001**
Trial Type:PSim3	0.368	0.19	1.96	**.049**
Language Status:log(Block):Phonological Similarity				
Language Status:log(Block):PSim1	0.109	0.09	1.19	.201
Language Status:log(Block):PSim2	0.001	0.09	-0.02	.987
Language Status:log(Block):PSim3	-0.053	0.15	-0.42	.732
Language Status:log(Block):Trial Type	0.063	0.07	0.45	.371
Language Status:Phonological Similarity:Trial Type				
Language Status:PSim1:Trial Type	0.299	0.20	1.58	.128
Language Status:PSim2:Trial Type	0.202	0.19	1.07	.298
Language Status:PSim3:Trial Type	0.242	0.35	0.72	.490
Log(Block):Phonological Similarity:Trial Type				
log(Block):PSim1: Trial Type	-0.163	0.10	-1.59	*.092*
log(Block):PSim2: Trial Type	0.089	0.10	1.03	.347
log(Block):PSIm3: Trial Type	-0.025	0.17	-0.11	.883
Language Status:log(Block):Phonological Similarity:Trial Type				
Language Status:log(Block):PSim1:Trial Type	-0.031	0.17	-0.24	.856
Language Status:log(Block):PSim2:Trial Type	-0.211	0.17	-1.29	.215
Language Status:log(Block):PSim3:Trial Type	-0.244	0.31	-0.85	.427

Table 6.3 continued.

Random Parts	
$\tau_{00, Participants}$	1.62
$\tau_{00, Concepts}$	1.017
$N_{Participants}$	63
$N_{Concepts}$	60
$ICC_{Participants}$	0.273
$ICC_{Concepts}$	0.172
Observations	72325
Tjur's D	.378
AIC	68442.873

     6.4.1.3 Response Latencies. The coefficients for the LMM model fit to response

latencies are presented in Table 6.4. Figure 6.4 shows the data extracted from this model in

two ways. Response speed increased over blocks with greater increases for correct

identification of targets relative to foils, overall [log(Block); log(Block):Trial Type]. High

similarity trials produced faster response latencies, which was particularly pronounced for

responses to targets (Phonological Similarity; Phonological Similarity:Trial Type]. The

overall response latencies for low similarity targets were similar for targets and foils.

Language status did affect response latencies. Overall, the bilingual group's response speed

increased over blocks to a greater extent than monolinguals [Language Status:log(Block)].

Despite similar response latencies in block 1, bilingual become increasingly faster across

blocks in relation to monolinguals, particularly for correct rejection of foils [Language

Status:log(Block):Trial Type]. The relative differences in response latency slopes over blocks

can be seen more clearly in Figure 6.4B.
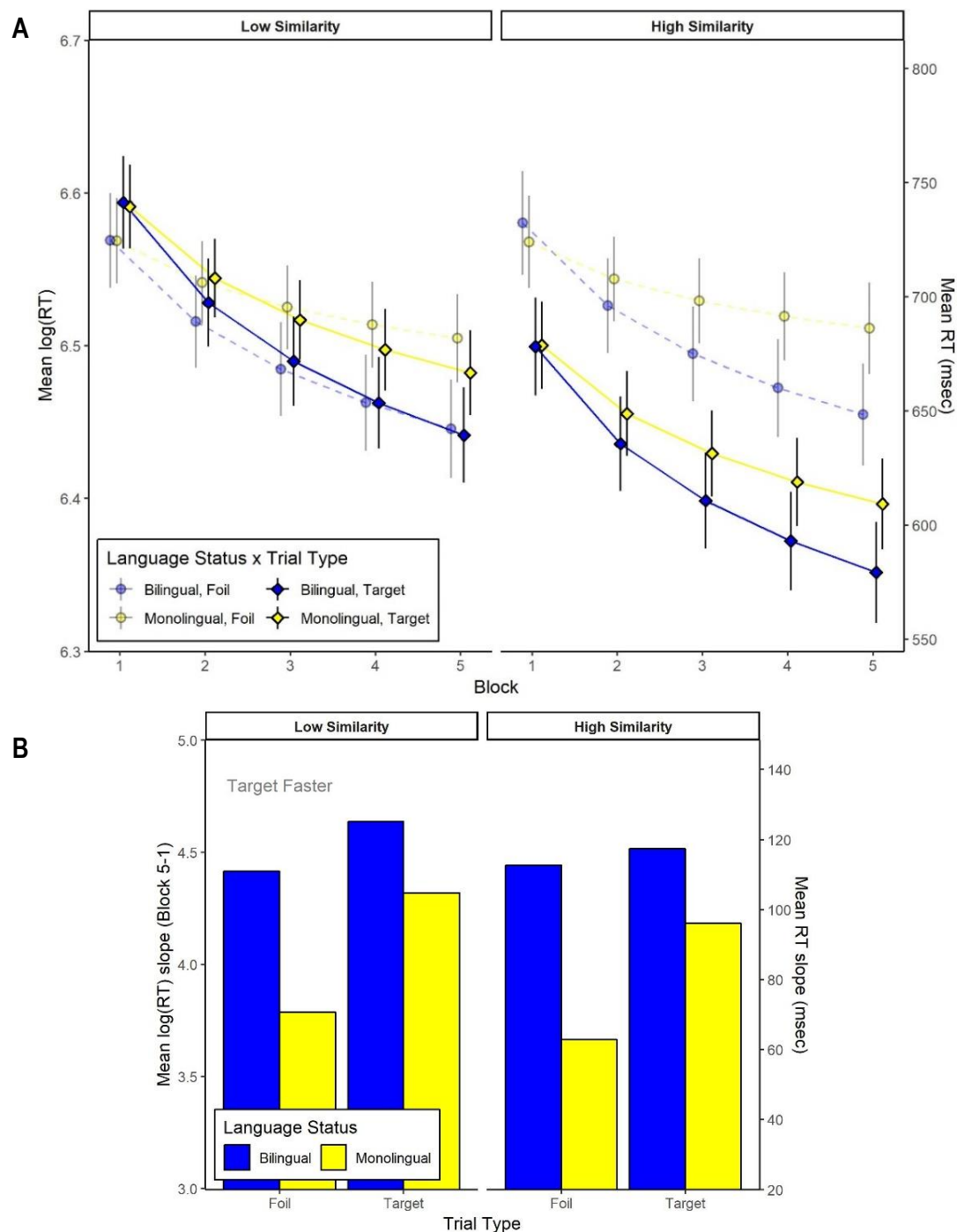
Figure 6.4. Mean log response latencies and 95% CIs as a function of Block and Language Status, panelled by phonological similarity (A). Response latency slopes calculated for additional information (B). Exponentiated response latencies in milliseconds for reference on right axis.

Table 6.4.

Model Coefficients for LMM Fit to Log-Transformed Response Latencies.

	B	95% CI	t	p
(Intercept)	6.564	6.54 – 6.58	615.60	**<.001**
Language Status (Monolingual, Bilingual)	-0.003	-0.04 – 0.03	-0.20	.848
log(Block)	-0.066	-0.07 – -0.06	-17.30	**<.001**
Phonological Similarity (Low, High) [Psim]	-0.043	-0.05 – -0.03	-8.90	**<.001**
Trial Type (Foil, Target)	-0.014	-0.03 – 0.00	-1.70	.095
Language Status:log(Trial)	0.033	0.02 – 0.05	4.50	**<.001**
Language Status:Psim	-0.005	-0.02 – 0.01	-0.50	.606
log(Block):Psim	0.002	-0.00 – 0.01	0.70	.465
Language Status:TrialT ype	0.004	-0.03 – 0.04	0.20	.831
log(Block):Trial Type	-0.023	-0.03 – -0.02	-7.60	**<.001**
PSim:TrialType	-0.097	-0.11 – -0.08	-12.80	**<.001**
Language Status:log(Block):PSim	0.003	-0.01 – 0.02	0.50	.611
Language Status:log(Block):Trial Type	-0.012	-0.02 – -0.00	-2.00	**.046**
Language Status:PSim:Trial Type	0.016	-0.01 – 0.04	1.10	.281
log(Block):PSim:Trial Type	0.001	-0.01 – 0.01	0.10	.887
Language Status:log(Block):PSim:Trial Type	-0.006	-0.03 – 0.02	-0.40	.655

Random Parts

σ^2	0.025
$\tau_{00, Participants}$	0.015
$\tau_{00, Concept}$	0.004
ρ_{01}	-0.147
$N_{Participants}$	63
$N_{Concept}$	60
$ICC_{Participants}$	0.346
$ICC_{Concept}$	0.091
Observations	49486
R^2	.315
AIC	-41432.49

6.4.2 Backward Translation

One datafile for List A, Day After, and its corresponding audio file was lost due to a technical error and could not be recovered. In total, there were 20,940 observations in the translation task dataset. An additional 21 trials were excluded (0.01%; remaining 20,921) because of technical errors (e.g., audio file stuttered half-way through, participant coughed during stimulus presentation). Fourteen participants failed to attend the follow-up sessions

[Monolingual = 10 (28.5%), Bilingual = 4 (14%)], so data from only 49 participants are included in the model at this time point.

The random effects structure for the parsimonious GLMM included a by-participant intercept and within-participant slopes of Session and RawPNLD quartile, plus a random intercept for concept and within-concept slope of Language Status. Random effects correlations substantially improved the model fit ($AIC_{DIFF} = 370.90$). We refit this model with accuracy based on a more lenient coding scheme, where suitable alternative responses were included as correct (e.g., feather rather than wing in response to /vleugel/). The pattern of coefficients was consistent between both models, but the more lenient model resulted in a slightly worse fit ($AIC_{LENIENT} = 19052.54$), compared to the strict model ($AIC_{STRICT} = 18915.79$). Residuals from both models showed departure from uniformity ($p < .001$) but there was no evidence significant dispersion from the expected distribution (both $p > .75$). The strict model was adopted because of the slightly better fit to the data. Model coefficients for the strict model can be found in Table 6.5 and data presented in Figure 6.5. Coefficients for the lenient model and comparable figures are presented in Appendix B.

Overall, translation success was highly variable and performance decreased between sessions (Session). Figure 6.5 clearly shows translation accuracy increased exponentially as a function of phonological similarity band – there was little advantage for items in Band 2 over items in Band 1 but for items with moderate phonological overlap in Band 3, there was a substantial increase in translation accuracy of around 18% on average compared to the previous band, with an additional average gain of approximately 22% accurate responses for items with the greatest phonological overlap. The pattern of decay over sessions was consistent at all levels of phonological similarity (Session:Phonological Similarity) and, response patterns were not moderated by language status.
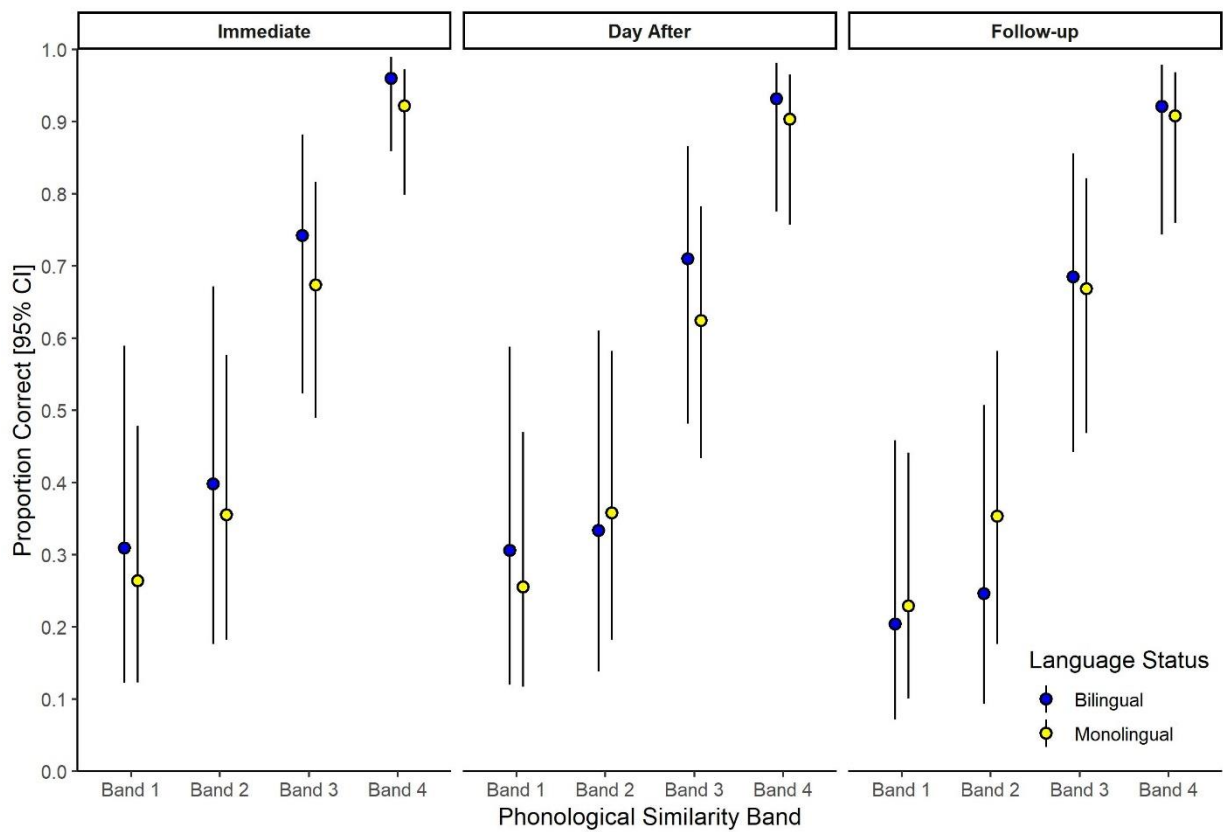
Figure 6.5. Proportion correct translation responses and 95% CIs separated by phonological

similarity band, Session and Language Status.

Table 6.5.

Parsimonious GLMM model estimates for translation accuracy.

	lnOR	*95% CI*	*z*	*p*
(Intercept)	0.30	-0.21 – 0.82	1.154	.248
Language Status	-0.17	-0.61 – 0.26	-0.774	.439
Session				
Immediate vs. Day After [Session1]	-0.18	-0.31 – -0.05	-2.704	**.007**
Day After vs. Follow-up [Session2]	-0.15	-0.35 – 0.06	-1.373	.170
Phonological Similarity				
Band 1 vs. Band 2 [PSim1]	0.37	-1.01 – 1.74	0.525	.600
Band 2 vs. Band 3 [PSim2]	1.45	0.20 – 2.70	2.275	**.023**
Band 3 vs. Band 4 [PSim3]	1.78	0.35 – 3.21	2.441	**.015**
Language Status:Session				
Language Status:Session1	0.10	-0.15 – 0.35	0.784	.433
Language Status:Session2	0.34	-0.07 – 0.75	1.607	.108
Language Status:Phonological Similarity				
Language Status:PSim1	0.25	-0.47 – 0.96	0.675	.500
Language Status:PSim2	-0.40	-1.03 – 0.23	-1.233	.217
Language Status:PSim3	-0.17	-0.95 – 0.61	-0.421	.674
Session:Phonological Similarity				
Session1:PSim1	-0.12	-0.35 – 0.12	-0.956	.339
Session2:PSim1	0.12	-0.15 – 0.38	0.858	.391
Session1:PSim2	-0.04	-0.27 – 0.18	-0.368	.713
Session2:PSim2	0.27	0.02 – 0.51	2.118	**.034**
Session1:PSim3	-0.23	-0.52 – 0.07	-1.512	.130
Session2:PSim3	-0.09	-0.39 – 0.22	-0.542	.588
Language Status:Session:Phonological Similarity				
Language Status:Session1:PSim1	0.32	-0.15 – 0.78	1.338	.181
Language Status:Session2:PSim1	0.01	-0.51 – 0.54	0.045	.964
Language Status:Session1:PSim2	-0.34	-0.78 – 0.09	-1.536	.124
Language Status:Session2:PSim2	-0.10	-0.58 – 0.38	-0.404	.686
Language Status:Session1:PSim3	0.39	-0.19 – 0.97	1.322	.186
Language Status:Session2:PSim3	-0.10	-0.71 – 0.50	-0.334	.738
Random Parts				
$\tau_{00, Participants}$				0.578
$\tau_{00, Concepts}$				3.492
ρ_{01}				0.386
$N_{Participants}$				63
$N_{Concepts}$				60
$ICC_{Participants}$				0.079
$ICC_{Concepts}$				0.474
Observations				20925
Tjur's D				0.445
AIC				18915.791

6.4.2.1 Error Rates. To provide additional insight into the nature of responses in both groups, error rates were extracted as a proportion of total trials for each participant, in each instance of the task (Figure 6.6; Table 6.6). Errors were coded into seven overarching categories:

- Alternative responses: Potentially correct using a more lenient criteria (e.g., feather instead of wing in response to /vleugel/ [wing]).

- Don't Know: "Don't know" or failure to respond

- Phonological Errors: Responses were considered phonological errors if a participant produced an incorrect but phonologically related response to the target word in English. Examples included the response "beer" to the target /peer/ [pear] or "scarf" in response to /schaap/ [sheep]. Other types of phonological error included confusion between phonologically similar Dutch targets. For example, participants produced "thumb" in response to /doos/ [box] via possible confusion with the Dutch word for thumb /duim/ (similar vowel sounds). Similar errors for /draad/ [wire] were recorded where participants responded 'grapes' [druif] or between naald [needle] and draad [wire].

- Semantic: Response where another category exemplar was produced in response to the target. For example, "coat" in response to /jurk/ [dress] or "arm" in response to /been/ [leg].

- Mixed: More complex errors where the route to the response is via phonology and semantics. For example, the response 'cow' in response to 'muur' [wall]. Cow is target concept in one of the lists and this error may arise via coactivation of 'moo' by /muur/ and the residual activation of 'cow.'

- Visual: Incorrect label for an object that could not be construed as part or whole object extraction or reasonable confusability error. For example, "donkey" instead of "horse" in response to /paard/ [horse].

- Unrelated: Participant produced an incorrect response not related to the correct translation through phonology, semantics or through visual error, an obvious guess. For example, in response to the Dutch target /geweer/ [gun] a participant responded "snow" [sneeuw].

Overall, Don't know errors were most frequent, followed by Phonological and Unrelated errors, with similarly low rates of Semantic, Mixed and Visual errors. As is clear in Figure 6.6, the distribution of error types was similar for monolinguals and bilinguals overall. However, monolinguals tended to produce more Don't Know errors relative to bilinguals who tended to produce more Phonological errors at Follow-up.
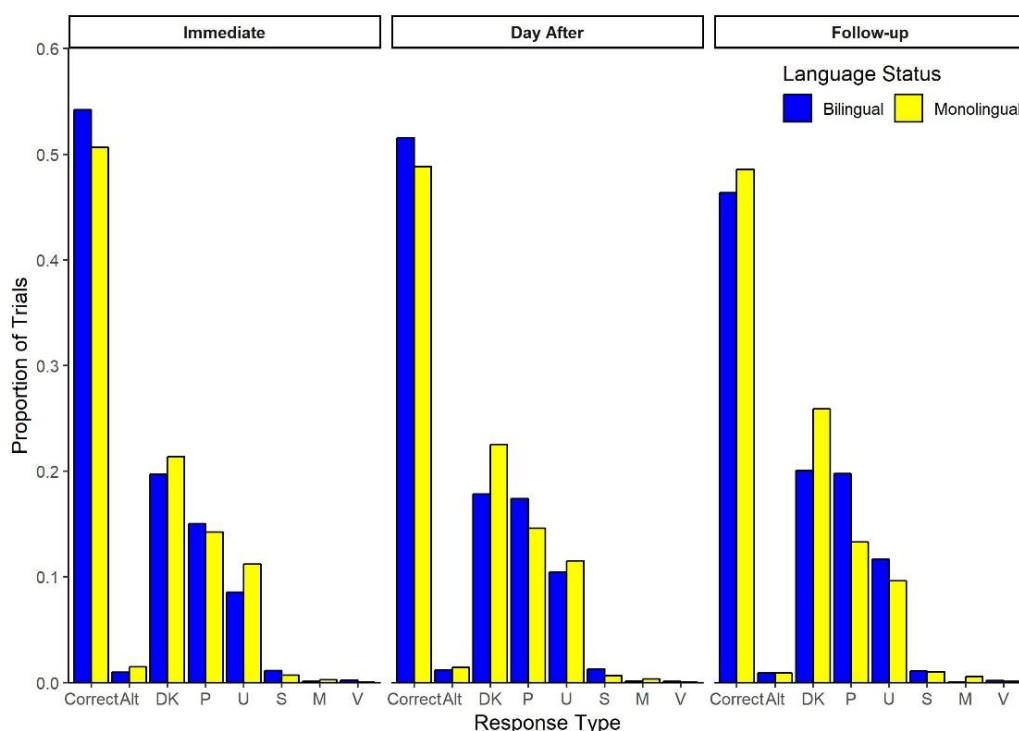
Figure 6.6. Proportion of trials per response type split by Session and Language Status. Alt: Alternative; DK = Don't know; P = Phonological; U = Unrelated; S = Semantic; M = Mixed; V = Visual.

Table 6.6.

Proportion Trials per Response Type Split by Session and Language Status.

| | Response Type | | | | | | | |
	Correct	Alt	DK	P	U	S	M	V
Bilingual								
Immediate	0.542	0.010	0.197	0.151	0.086	0.011	0.001	0.002
Day After	0.516	0.012	0.178	0.174	0.105	0.013	0.001	0.001
Follow-up	0.464	0.009	0.200	0.198	0.117	0.011	0.000	0.002
Monolingual								
Immediate	0.506	0.015	0.214	0.143	0.112	0.007	0.003	0.000
Day After	0.488	0.014	0.225	0.146	0.115	0.007	0.003	0.000
Follow-up	0.486	0.009	0.259	0.133	0.096	0.010	0.006	0.001

6.4.3 Interim summary

Increasing phonological similarity biased participants to make more 'match' response from block 1 of the task but repetition of consistent word-picture pairs resulted in a general learning effect over and above this bias. Although bilinguals did not show an advantage in associative learning on measures of discrimination accuracy, they did show a steeper reduction in response latencies relative to monolinguals that was particularly pronounced when rejecting competing foils. In translation, the phonological similarity bias prevailed with increasing success for targets in higher similarity bands. There was no bilingual advantage in retention or consolidation on this task but there was a trend towards a different error profile for the two groups.

6.4.4 Moderating Effects of Phonological Memory

In this study, a secondary aim was to examine whether a proposed advantage in phonological working memory might underpin an advantage in word learning in bilingual participants. Although we did not set out to control phonological working memory abilities, nevertheless the two groups of participants did not differ on this measure, ruling out this

explanation. On the other hand, it is possible that phonological working memory performance

could moderate the bilingual advantage we observed in RTs in some other way, as some

reports suggest a general role for phonological working memory in word learning ability

overall. The phonological memory composite scores collected from our sample were tightly

clustered between 90 and 110, potentially restricting the sensitivity of any analyses including

this variable. The distribution of scores for memory for digits and nonword repetition subtests

were much more variable. Exploratory correlations revealed more consistent relationships

between scaled scores on forward digit span and response times in block 5, compared to

nonword repetition or phonological memory composite scores (Table 6.7). This pattern of

correlations was consistent at both levels of phonological similarity and suggested that better

digit span performance was associated with faster responses in block 5 to targets and slower

response times to foils. Considering these findings, we limited our exploration of

phonological memory performance on learning to the memory for digits subtest scaled

scores. Due to the consistent size of correlation coefficient at each level of Phonological

Similarity and across foils and targets, and no apparent processing difference between

monolinguals and bilinguals in response to phonological similarity we dropped phonological

similarity as a fixed effect from this model.

Table 6.7.

Exploratory Correlations Between Phonological Memory Composite Scores, Subtest Scores,

log(RT) in Block 5, Separated by levels of Phonological Similarity and Trial Type.

Trial Type	Phonological Similarity	Phonological Working Memory Composite	Memory for Digits Scaled Scores	Nonword Repetition Scaled Scores
Foil	Low	0.06	0.18	-0.06
	High	0.08	0.22	0.00
Target	Low	-0.09	-0.17	-0.02
	High	-0.07	-0.14	0.02

We present the response latencies first as this is the measure that revealed a bilingualism advantage earlier. Mean-centred Memory for Digits scores were entered as a continuous fixed effect along with Language Status, log(Block) and Trial Type. A random intercept of participant was retained with a random slope for Trial Type and log(Block). The random intercept for concepts was retained with random slopes of Language Status and log(Block). Coefficients are present in Table 6.8 with data displayed in Figure 6.7A. Memory for digits scores did moderate reaction time patterns. More specifically, it interacted with trial type such that there was a larger difference in latencies between targets and foils with increasing Memory for Digits scores. Crucially however, the bilingual advantage in response times was not moderated by phonological working memory, as none of the interactions with language status were significant. A parallel analysis was conducted on the 'match' response data (see Table 6.9). This analysis showed a positive association between memory for digits scores and overall proportion of match responses. Additionally, there was a trend for greater phonological working memory scores to be associated with better learning, as indexed by greater relative deviation between targets and foils over blocks (Figure 6.7B).

Finally, Memory for Digits scores were added as a fixed effect to the model for translation data (Table 6.10; Figure 6.8), excluding phonological similarity from the analysis. Higher Memory for Digit scores were associated with greater overall translation success (Memory for Digist) and better short- but not long-term maintenance of performance (Memory for Digits:Session). Furthermore, there was a weak trend towards greater decay for bilinguals over the follow-up period (Immediate: 0.63, $SE = 0.35$; Day After: 0.61, $SE = 0.35$; Follow-up: 0.54, $SE = 0.35$), relative to monolinguals (Immediate: 0.55, $SE = 0.29$; Day After: 0.52, $SE = 0.29$; Follow-up: 0.50, $SE = 0.29$).

Table 6.8.

LMM Coefficients Including the Moderating Effect of Memory for Digits on Response

Latencies

	B	*95% CI*	*t*	*p*
(Intercept)	6.554	6.53 – 6.58	602.672	**<.001**
Memory for Digits [MfD]	0.004	-0.00 – 0.01	1.007	.318
Language Status (Monolingual, Bilingual)	-0.004	-0.04 – 0.03	-0.273	.786
log(Block)	-0.065	-0.07 – -0.06	-17.594	**<.001**
Trial Type (Foil, Target)	-0.034	-0.05 – -0.02	-4.348	**<.001**
MfD:Language Status	-0.010	-0.02 – 0.00	-1.368	.176
MfD:log(Block)	-0.002	-0.01 – 0.00	-1.503	.138
MfD:Trial Type	-0.011	-0.02 – -0.00	-3.065	**.003**
Language Status:log(Block)	0.033	0.02 – 0.05	4.662	**<.001**
Language Status:Trial Type	0.007	-0.02 – 0.04	0.414	.680
log(Block):Trial Type	-0.020	-0.03 – -0.01	-7.48	**<.001**
MfD:Language Status:log(Block)	-0.003	-0.01 – 0.00	-1.015	.314
MfD:Language Status:Trial Type	0.003	-0.01 – 0.02	0.364	.717
MfD:log(Block):Trial Type	0.000	-0.00 – 0.00	-0.174	.862
Language Status:log(Block):Trial Type	-0.010	-0.02 – 0.00	-1.827	***.068***
MfD:Language Status:log(Block):Trial Type	0.003	-0.00 – 0.01	1.168	.243

Random Parts				
σ^2				0.025
$\tau 00_{,\ Participants}$				0.011
$\tau 00_{,\ Concept}$				0.004
ρ_{01}				-0.134
$N_{Participants}$				63
$N_{Concept}$				60
$ICC_{Participants}$				0.266
$ICC_{Concept}$				0.108
Observations				49466
R^2				0.299
AIC				-40494.428

Table 6.9.

GLMM Coefficients including Moderating Effect of Memory for Digits on Match Responses

	lnOR	*95% CI*	*z*	*p*
(Intercept)	-0.27	-0.54 – -0.00	-1.99	**.046**
Language Status	-0.03	-0.30 – 0.24	-0.21	.837
Memory for Digits	0.07	0.01 – 0.13	2.3	**.022**
log(Block)	0.18	0.05 – 0.30	2.78	**.005**
Trial Type	1.36	1.21 – 1.50	18.32	**<.001**
Language Status:MfD	-0.09	-0.21 – 0.02	-1.57	.116
Language Status:log(Block)	0.04	-0.19 – 0.27	0.31	.754
Language Status:Trial Type	-0.24	-0.53 – 0.06	-1.59	.112
MfD:log(Block)	0.02	-0.03 – 0.08	0.91	.362
MfD:Trial Type	0.05	-0.01 – 0.12	1.59	.112
log(Block):Trial Type	0.78	0.69 – 0.87	16.93	**<.001**
Language Status:MfD:log(Block)	0.00	-0.10 – 0.10	0.00	.999
Language Status:MfD:Trial Type	0.06	-0.07 – 0.19	0.87	.382
Language Status:log(Block):Trial Type	0.04	-0.13 – 0.22	0.48	.633
MfD:log(Block):Trial Type	0.04	-0.00 – 0.08	1.81	*.071*
Language Status:MfD:log(Block):Trial Type	-0.06	-0.14 – 0.02	-1.41	.159

Random Parts

$\tau 00$, Participants	0.76
$\tau 00$, Concept	1.41
$N_{Participants}$	63
$N_{Concept}$	60
$ICC_{Participants}$	0.14
$ICC_{Concept}$	0.25
Observations	72325
Tjur's D	0.324
AIC	74858.36
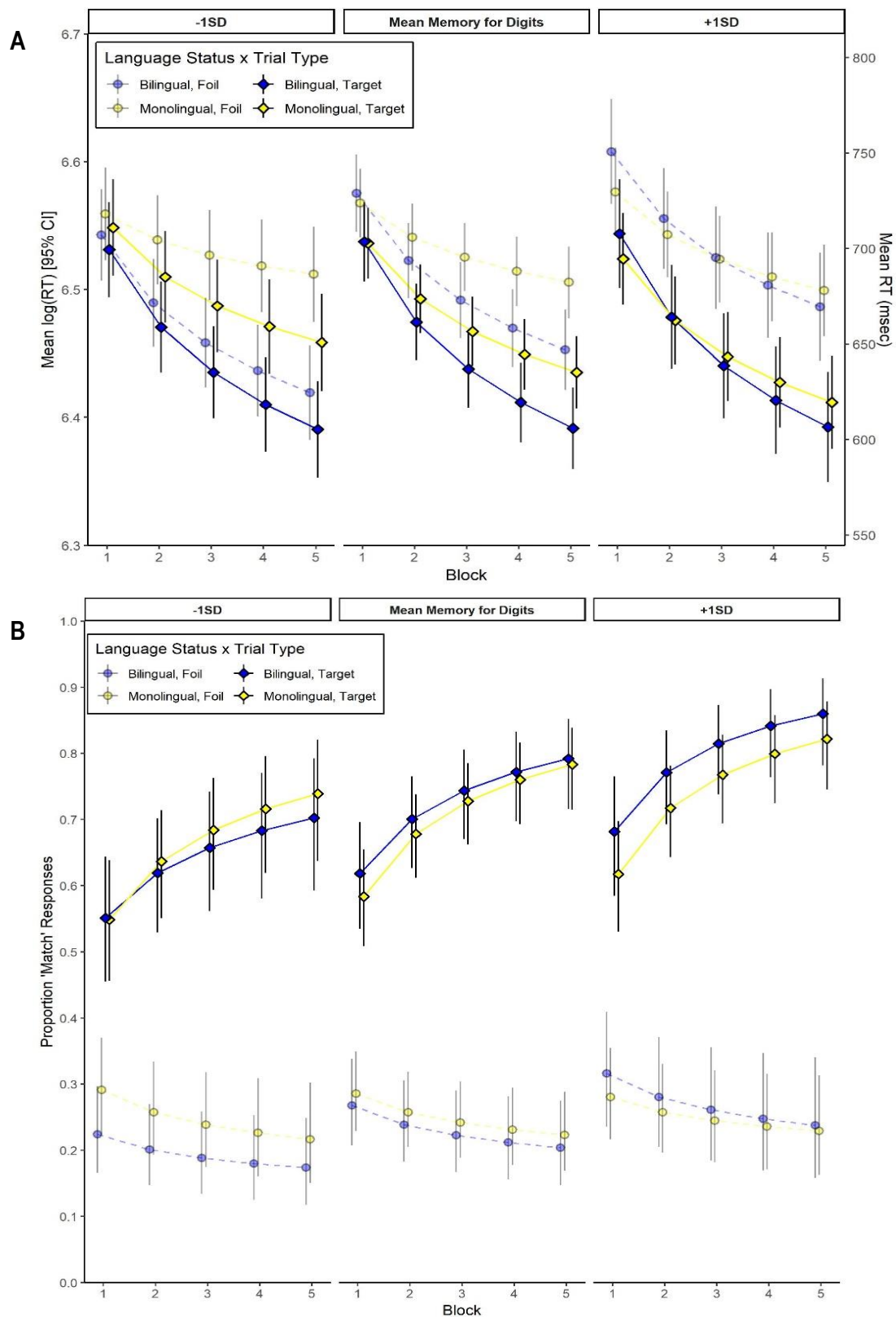
Figure 6.7. Moderating effects of Memory for Digits performance on learning performance

for A) log response latencies (95% CI) and B) proportion 'Match' responses (95% CI).

Table 6.10.

GLMM Including Memory for Digits as a Moderator of Translation Performance.

	lnOR	*95% CI*	*z*	*p*
(Intercept)	0.26	-0.33 – 0.86	0.87	.382
Language Status (Monolingual, Bilingual)	-0.30	-0.70 – 0.10	-1.46	.144
Memory for Digist (MfD)	0.16	0.09 – 0.24	4.14	**<.001**
Session				
Immediate vs. Day After (Session1)	-0.11	-0.20 – -0.02	-2.36	**.018**
Day After vs. Follow-up (Session2)	-0.19	-0.30 – -0.09	-3.51	**<.001**
Language Status:MfD	-0.04	-0.20 – 0.11	-0.54	.591
Language Status:Session				
Language Status:Session1	-0.01	-0.19 – 0.17	-0.15	.883
Language Status:Session2	0.20	-0.01 – 0.42	1.86	*.063*
Memory for Digits:Session				
MfD:Session1	0.04	0.00 – 0.08	2.02	**.043**
MfD:Session2	-0.00	-0.05 – 0.04	-0.21	.833
Language Status: Memory for Digits:Session				
Language Status:MfD:Session1	-0.02	-0.10 – 0.05	-0.61	.542
Language Status:MfD:Session2	-0.01	-0.10 – 0.08	-0.30	.762
Random Effects				
τ_{00} Participants				0.46
τ_{00} Concepts				4.97
$N_{Participants}$				63
$N_{Concepts}$				60
ICC Participants				0.05
ICC Concepts				0.57
Observations				20940
Tjur's *D*				.428
AIC				19017.29
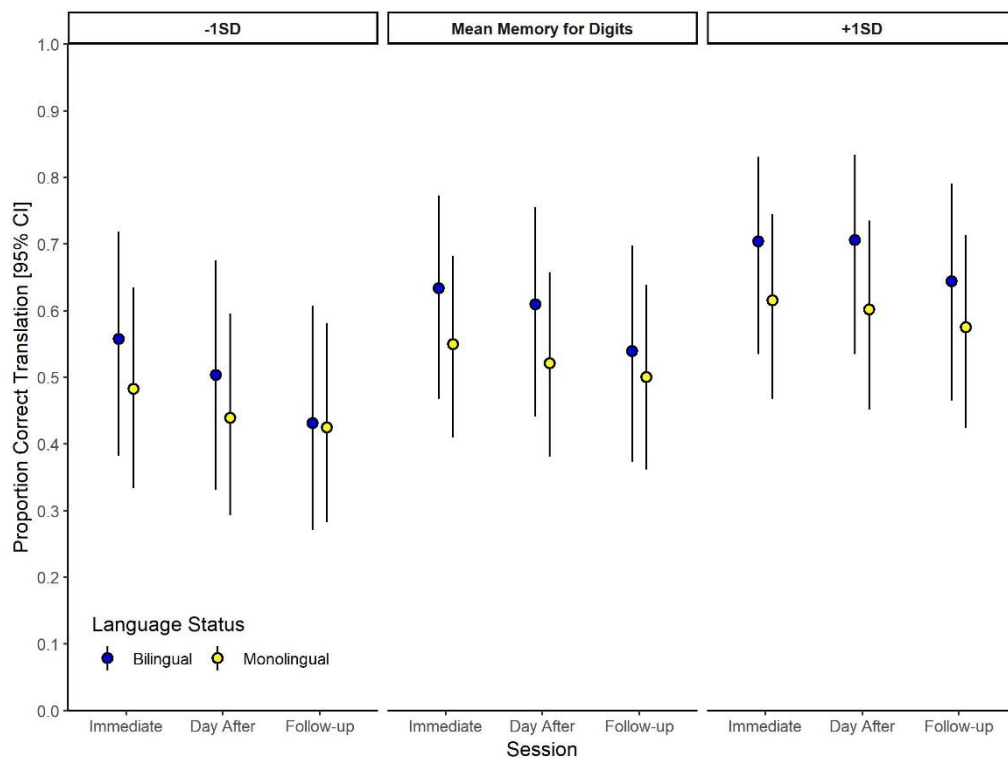
Figure 6.8. Proportion of correct responses [95% CI] on the translation task split by session for both Monolingual and Bilingual participants, and panelled by levels of Memory for Digits scores.

6.4.5 Processing Speed and Everyday Language Switching.

As described in the previous section, the bilingual advantage observed on reaction times in the learning task cannot be explained by differences in phonological memory. Alternatively, a bilingual advantage in word learning could derive from enhanced executive control linked to the management and control of two languages. In the present study bilingual participants completed the BSWQ, which is a measure of everyday language switching behaviour that has been shown to predict the size of mixing costs in non-linguistic executive control tasks in a bilingual sample (Soveri et al., 2011). The scores were normally distributed around the mean ($M = 33.43$, $SD = 5.63$) with a minimum total switching score of 24 and a maximum of 43, roughly at the extremes of possible values, providing a good range for use as a continuous moderating variable. We examined whether the pattern of response times

observed in the learning task was moderated by self-reported language switching behaviours

by using the overall switching scores from the BSWQ as a proxy for language control. A

direct comparison with monolinguals in this instance is difficult given that the BSWQ is a

continuous variable. Sub-setting the bilinguals into bands of switching behaviours would

results in low sample numbers, making estimates difficult to interpret. However, estimates for

the monolinguals are presented for visual comparison in the figures below.

Models conducted on discrimination and response latency data, restricted to bilingual

participants were constructed with fixed effects of log(Block), TrialType and a mean-centred

continuous predictor of Overall Switching scores from the BSWQ. We included phonological

working memory as a covariate to control for the influence of this factor on general learning

ability. A random intercept for participants was included with a slope of log(Block) and Trial

Type plus a random intercept for concepts and a within-concept slope of log(Block).

Estimates for both models are included in Table 6.11.

The analysis of discrimination data revealed that participants who switched more

often produced more match responses overall [Trial Type]. Switching tendencies did not

modify any of the more complex effects. Figure 6.9 includes a comparison with the

monolingual learning data collapsed over phonological similarity of the stimuli. Visual

inspection of the plot appears to show a trend for better learning performance by bilinguals at

all switching levels, greatest for high switchers. This is most notable in the wider separation

between the proportion of hits to targets and proportion of false alarms to foils. However, this

general trend was not observed in the earlier analysis, separated by phonological similarity.

For response latencies, there was a significant moderation effect of overall switching

behaviours on the relative slopes to foils and targets [BSWQ:log(Block):Trial Type]. The

higher the switching scores, the larger the difference between foils and targets over blocks. In

Figure 6.10, data from monolinguals are included for comparison. It is clear that bilinguals in general show much steeper improvements in speed relative to monolinguals for both foils and targets.

Table 6.11.

GLMM and LMM Estimates for a Moderating Effect of Switching Behaviour on Bilingual Learning Performance for Discrimination and Response Latency Data.

	Discrimination				Response Latencies			
	lnOR	*95% CI*	*z*	*p*	*B*	*95% CI*	*t*	*p*
(Intercept)	-0.25	-0.56 – 0.06	-1.59	.112	6.560	6.52 – 6.59	405.28	**<0.001**
Memory for Digits	0.10	0.03 – 0.18	2.65	**.008**	0.010	-0.00 – 0.02	1.41	.170
BSWQ Overall Switching	0.08	0.02 – 0.14	2.53	**.011**	0.010	-0.00 – 0.02	1.10	.282
log(Block)	0.13	0.02 – 0.24	2.28	**.022**	-0.080	-0.09 – -0.07	-14.68	**<.001**
Trial Type	1.50	1.18 – 1.82	9.26	**<.001**	-0.040	-0.06 – -0.01	-2.67	**.012**
BSWQ:log(Block)	0.01	-0.03 – 0.04	0.39	.697	0.000	-0.00 – 0.01	0.83	.415
BSWQ:Trial Type	0.04	-0.07 – 0.15	0.72	.474	0.000	-0.01 – 0.01	0.09	.926
log(Block):TrialType	0.71	0.60 – 0.81	13.68	**<.001**	-0.010	-0.02 – -0.00	-3.17	**.002**
BSWQ:log(Block):Trial Type	0.02	-0.01 – 0.06	1.23	.218	0.000	-0.01 – -0.00	-3.03	**.002**
Random Effects								
σ^2				3.29				0.03
$\tau_{00\ \text{Concepts}}$				1.02				0
$\tau_{00\ \text{Participants}}$				1.45				0.01
N_{Concepts}				60				60
$N_{\text{Participants}}$				28				28
ICC_{Concepts}				0.18				0.07
$ICC_{\text{Participants}}$				0.25				0.34
Observations				31874				21815
Tjur's D/R2				.346				.467
AIC				32183.333				-17811.893
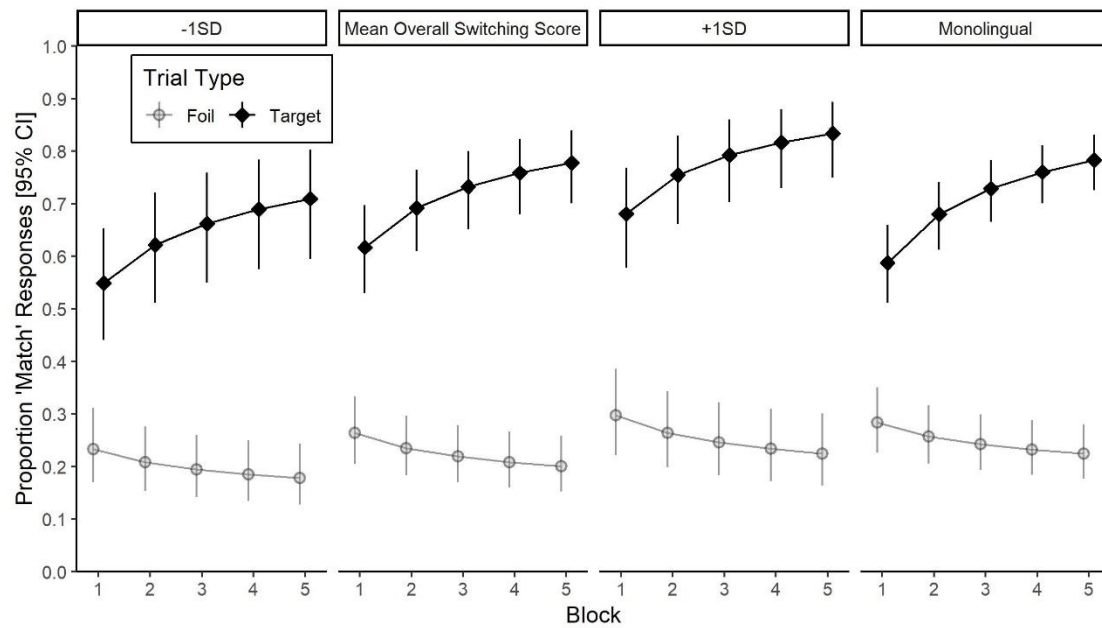
Figure 6.9. Proportion of 'match' responses (95% CI) for bilinguals only, separated by trial type and block and split at levels of everyday language switching. Effects of phonological memory were covaried out.
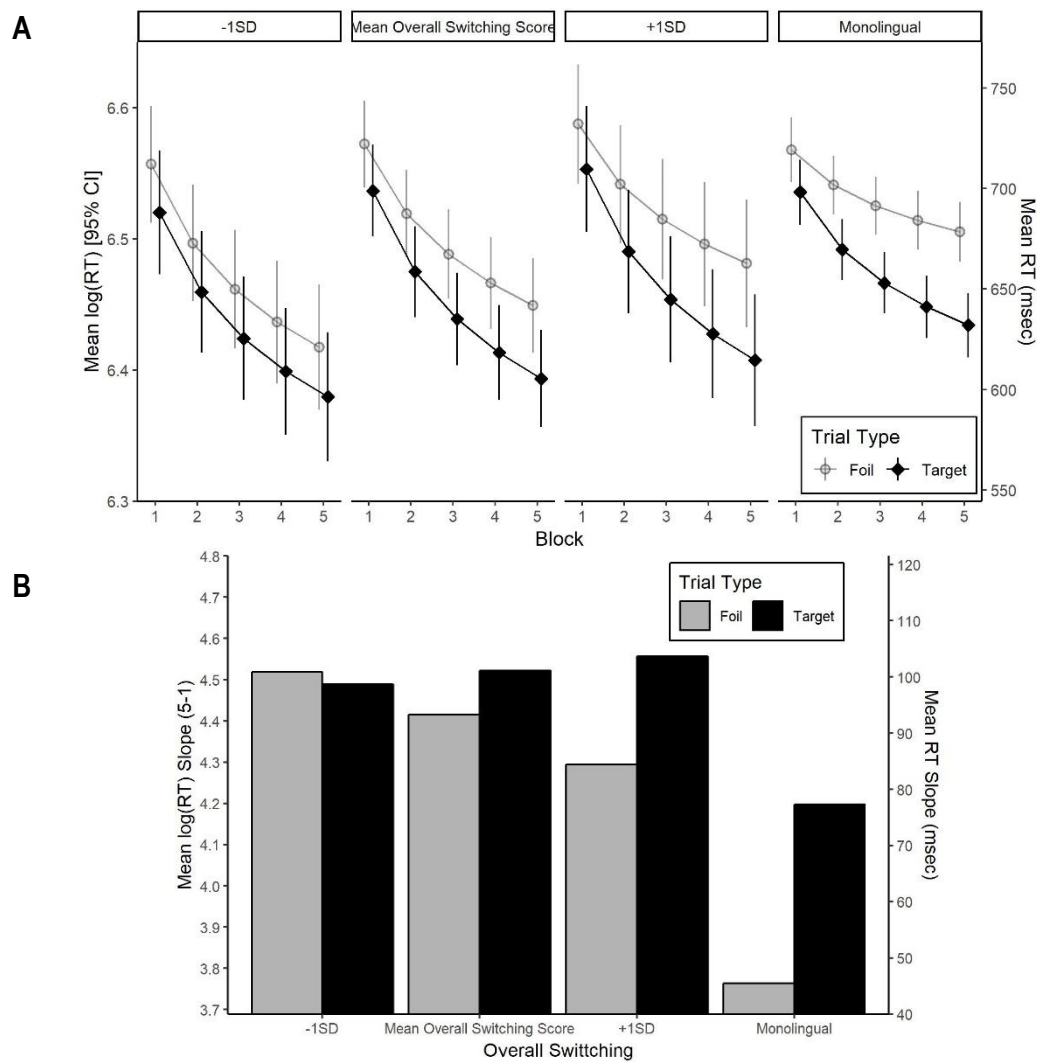
Figure 6.10. Estimates from LMM models for log response latencies [95% CI]. A) shows response latencies for each block, separated by target and foil trials for bilinguals, split at levels of everyday language switching (-1SD, Mean, +1 SD) plus monolingual data for comparison. B) Shows absolute log(RT) slopes (Block 5-1) for clearer depiction of slope size with larger values indiciating a greater increase in speed from block 1 to 5. Values on the right axis show exponentiated values for reference to untransformed response latencies. Effects of phonological memory were covaried out.

To investigate the implications of this pattern for learning outcomes, a mixed model examining the effect of Overall Switching Scores was conducted on translation accuracy (Table 15). A fixed effect of Session was included in the model and allowed to interact with centred Switching Scores and included a between-participant intercept with slope for Session and a between-concept intercept. Centered memory for digits scores were included as a covariate for comparability with the above models for response latencies and discrimination data. This model did not reveal a significant moderating effect of Overall Switching on translation accuracy in general [BSWQ Overall Switching]. There was a trend towards an interaction between Overall Switching and Session that showed an advantage in translation accuracy for higher switchers immediately following learning but a steeper decline in performance over sessions to levels estimated for participants with relatively lower switching tendencies, by follow-up (rows 7-8, Table 6.12; Figure 6.11). Comparison with monolinguals in Figure 6.11 shows somewhat poorer performance for monolinguals relative to bilinguals at earlier time points but less of a decay in translation performance over later time points.
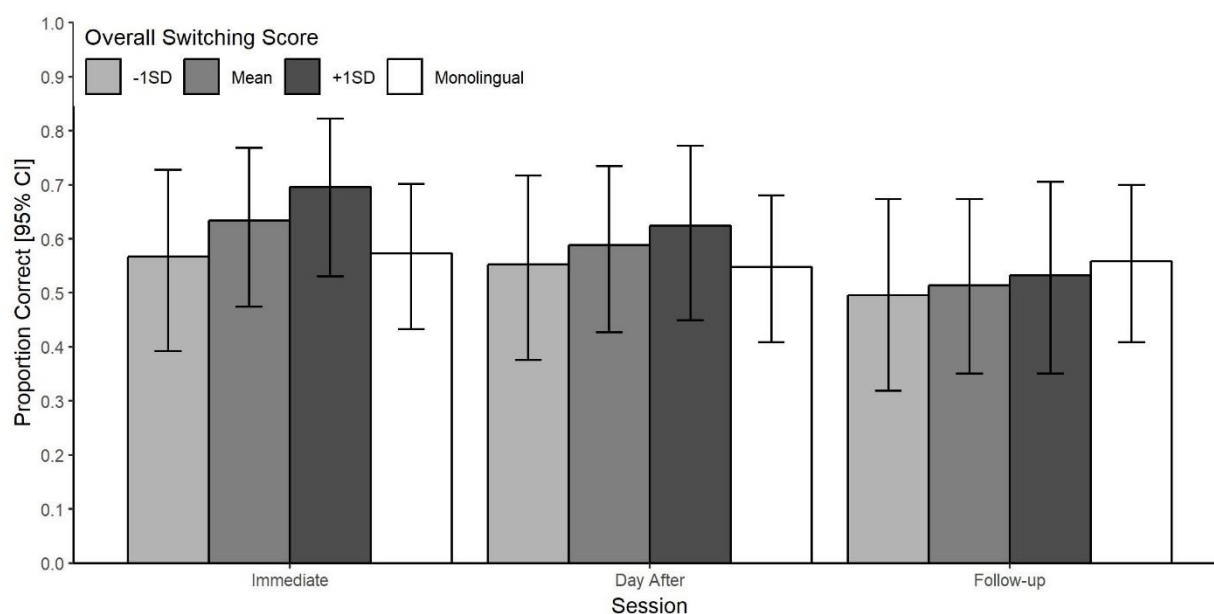
Figure 6.11. Proportion correct [95% CI] translation responses per session, split by levels of BSWQ overall language switching with monolingual estimates for comparison.

Table 6.12.

GLMM coefficients for translation accuracy with a moderator of overall switching tendency, controlling for Memory for Digits performance.

	lnOR	*95% CI*	*z*	*p*
(Intercept)	0.38	-0.27 – 1.03	1.15	.252
Memory for Digits	0.15	0.02 – 0.27	2.35	**.019**
BSWQ Overall Switching	0.06	-0.04 – 0.16	1.24	.215
Session: Immediate vs. Day After	-0.19	-0.34 – -0.04	-2.53	**.012**
Session: Day After vs. Follow-up	-0.30	-0.47 – -0.14	-3.71	**<.001**
BSWQ OS: Immediate vs. Day After	-0.05	-0.10 – 0.01	-1.72	**.086**
BSWQ OS: Day After vs. Follow-up	-0.03	-0.09 – 0.03	-0.92	.358

Random Effects	
σ^2	3.29
$\tau00_{Concept}$	5.39
$\tau00_{Participant}$	0.52
$ICC_{Concept}$	0.59
$ICC_{Participant}$	0.06
$N_{Concepts}$	60
$N_{Participants}$	28
Observations	9591
AIC	8379.622
Tjur's D	0.461

6.5 Discussion

The aim of the present study was to test for a bilingual advantage in lexical learning of real foreign language vocabulary. In addition to overall learning, the study compared the effects of the phonological similarity between Dutch targets and their English translation equivalents in English monolinguals and proficient Welsh-English bilinguals. Finally, the study examined moderating effects of phonological working memory and self-reported language switching behaviours on any possible bilingual advantage. The major findings are discussed in each section below.

6.5.1 Phonological Similarity

Phonological similarity had a consistent effect on performance for both groups during associative learning and translation. Increasing phonological similarity resulted in a bias to make more match responses from the outset of the associative learning task. This resulted in an increasingly greater base rate of hits and false alarms as a function in block 1 as function of increasing phonological similarity to English for targets and foils, respectively. This bias was also reflected in general response latencies to phonologically similar targets from the outset and more substantial improvement in speed of response over blocks, relative to phonologically dissimilar trials. In addition, translation success increased as phonological similarity between the Dutch target and its English translation increased. These response patterns were similar for both monolingual and bilingual participants. However, it is difficult to tell to what extent the effect of phonological similarity in translation success was affected by a cognate guessing strategy and in future measures of confidence judgements for translations would aid in evaluating true learning/consolidation of highly similar targets (e.g., (Otwinowska & Szewczyk, 2017). Nevertheless, the response patterns in learning and translation tasks both support the automatic cognate form assumption, in that phonological similarity of novel wordforms was used by the participants in this study to make initial inferences about meaning based on their existing knowledge of English, irrespective of whether they were engaged in learning a new L2 or L3 (Ecke & Hall, 2014; Hall, 2002, Lindsay & Gaskell, 2010). This result is consistent with a recent study by Nair, Biedermann and Nickels (2017) who reported similar effects of phonotactic probability and phonological neighbourhood density on novel pseudoword learning in monolingual English and bilingual Mandarin-English speakers, despite an overall bilingual advantage in word learning. These data taken together with results of the present study suggest that existing lexical knowledge

influences evaluation and assimilation of novel words in a similar manner for monolinguals and bilinguals, but that language experience may promote word learning success in general.

6.5.2 Learning did take place

Despite the substantial phonological similarity bias, participants were able to learn new words and translate from Dutch into English to a reasonable degree after just 20 minutes of exposure. Although true vocabulary learning takes places over months and years (for discussion Gupta & Tisdale, 2009) performance did improve in each subsequent block of trials for both groups of participants. The overall pattern of results is consistent with previous studies utilising this paradigm (Breitenstein et al., 2004, 2005; Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, et al., 2009; Flöel et al., 2008), demonstrating its utility for examination of word learning using targets from a real foreign language. In addition, the present study examined the response patterns to foil as a well as target trials, which provided more insight into the learning process than in previous studies that have focused on accurate responses to target pairs only. In the present study, hits to targets increased with exposure over blocks, whilst the relative rate of false alarms decreased, which is indicative of increasingly robust episodic representations of novel phonological-semantic connections (for discussion of the value of false alarms in recognition memory research, Wixted & Stretch, 2004). These data demonstrate further evidence for rapid acquisition of phonological-semantic mappings by adults through exposure to regular co-occurrences present in the environment (Breitenstein et al., 2004, 2005, 2007; Breitenstein & Knecht, 2002; Coutanche & Thompson-Schill, 2014; Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, et al., 2009; Havas et al., 2017; Yu & Smith, 2007). In addition, the present study showed that response latencies were also sensitive to increasing exposure and trial type. Despite relative ceiling effects in hits for the most phonologically similar targets, and relative floor effects in false alarms for phonologically dissimilar foils, speed of responses improved over blocks, particularly for

targets, indexing further learning. Previous studies using a similar paradigm have examined

changes in response latencies but as a simple by-product of task familiarity rather than as an

index of learning (Breitenstein & Knecht, 2002; Flöel et al., 2008). The present study shows

that response latencies may provide a subtler index of learning particularly, in cases of floor

or ceiling effects in accuracy, and where other psycholinguistic or task-level factors are

manipulated.

To probe word learning success and assimilation of form-meaning links, participants

completed backward translation tasks at three time points. We chose backward translation to

avoid potential ceiling effects that could arise in translation recognition tasks, particularly for

highly phonologically similar targets. On average, translation success was reasonable, but this

task was challenging for most participants and performance was highly variable. However,

performance was relatively stable over earlier sessions with a consistent decay over the week

follow-up period. The stability of the memory trace might suggest that engaging explicit

retrieval during translation may have solidified representations for successfully translated

targets but difficulty with other targets may have interfered with any further learning for

targets that could not be recalled. In future, additional learning sessions are needed to

strengthen representation of novel words and reduce variability on the translation task.

However, at this very early stage of word learning, backward translation may simply be too

difficult, masking subtler differences in performance between language groups overall in

consolidation and recall. Adopting a task that probes the engagement of new words in lexical

competition with known and unfamiliar novel words, may be one way of examining the

integration of new words into a participants' existing lexicon (e.g., Gaskell & Dumay, 2003).

6.5.3 Bilingual Advantage in Word Learning

In initial analyses, bilinguals showed a generalised advantage in decision times over

monolinguals, although there was no advantage in discrimination performance during

learning or in translation success. Decision speed started out at similar levels for both groups but bilinguals exceeded their monolingual counterparts in the speed of correctly accepting and rejecting targets and foils by the end of block five. Most studies have demonstrated a bilingual advantage in accuracy or total number of words recalled. In some previous studies, the bilingual advantage in response times has been observed in follow up tasks probing access to the newly learned words. For example, Bartolotti and Marian (2012) showed a generalised advantage for bilinguals in managing lexical competition effects for nearly learned words, despite training both groups to criterion on their novel vocabulary. In another study, Bradley, King and Hernandez (2013) showed that bilingual participants were faster than monolinguals to make semantic decisions about newly learned cognate and noncognate vocabulary, after just two-hours of exposure. From the present study, the generalised response time advantage *during* associative learning without feedback enriches a literature where the focus has been primarily on explicit learning tasks or focused solely on recall/recognition. The value of implicit tasks in this context comes in the form of less influence from inter-individual differences in appraisal of incoming information and rules-out strategic responding as a function of learning experiences (e.g., for late bilinguals learning an L2 in a classroom; van Hell & Mahn, 1997).

     6.5.3.1 Phonological working memory. Despite an increasing number of studies attesting to a generalised word learning advantage in bilinguals, the actual mechanisms that confer such an advantage are unclear. One prominent position has been the idea that a bilingual advantage in verbal working memory (Papagno & Vallar, 1995) may underpin the word learning advantage. In general, better verbal working memory performance is associated with more accurate word learning (Gathercole, 2006; Gupta & Tisdale, 2009a) but the proposed bilingual advantage in verbal working memory has not been demonstrated consistently. In fact, the bilingual advantage in word learning has been observed despite

controlling for phonological working memory performance in several studies (Kaushanskaya, 2012; Nair et al., 2016). The present study provides support for this latter position as the two groups of participants showed similar distributions of scores on the phonological working memory subtest form the CTOPP-2, ruling out this factor as a direct contributor to the word learning advantage. We did observe that better overall phonological working memory performance was associated with better discrimination in response profiles between targets and foils, for both accuracy and response latencies. A phonological working memory advantage does not appear to explain the bilingual advantage in word learning observed in this study.

6.5.3.2 Self-Reported Language Switching. Another potential factor that has been proposed to moderate language learning abilities in bilinguals, is cognitive control. In the present study, we collected self-reported frequency behaviours using the BSWQ (Soveri et al., 2011). Higher overall switching scores on the BSWQ have been associated with smaller mixing costs in non-linguistic switching tasks (Soveri et al., 2011; cf. Jylkkä, Soveri, Laine, & Lehtonen, 2019). More recent studies have shown that switching behaviours and not language proficiency may be the putative factor in explaining differences in cognitive control abilities amongst bilinguals (Verreyt et al., 2016) , which in turn may provide some explanation of the bilingual advantage in word learning (e.g., Bartolotti & Marian, 2012).

In the present study, an analysis was conducted that tested for moderating effects of switching behaviours on response latency patterns, within the bilingual group, to try to understand the nature of the bilingual advantage. At all levels of switching, bilinguals showed the generalised advantage in response time when compared to monolinguals. Within the bilingual group, self-reported switching tendencies were related to the degree of improvement in speed over the course of the task. The greatest improvements in speed over blocks were observed in participants who reported switching *less* often overall relative to average or high

propensity switchers within the sample. Furthermore, the relative speed improvements for

foils decreased with increasing switching scores; a response pattern more similar to the

English participants. On the latter point, higher switching bilinguals showed an initial

advantage in translation accuracy immediately following learning but a greater decay over

subsequent sessions, relative to lower switching bilinguals. What the mechanism is for such a

performance pattern is unclear at this stage and requires replication and investigation in a

much larger sample of bilinguals, so that other associated factors of bilingual experience can

be controlled or evaluated in more detail (e.g., language dominance, relative proficiency,

contextual use). What is clear is that switching behaviours do not explain the generalised

advantage in response time and there appears to be something more fundamental about using

and managing multiple languages that produces an advantage in word learning.

6.5.4 Alternative Explanation

There is growing evidence that long-term experience of using and managing multiple

languages has consequences for structure and connectivity in the brain relative to

monolinguals (Hayakawa & Marian, 2019). However, much of the focus of studies testing for

a bilingual advantage in language learning has been on cognitive and contextual factors (for

recent up-to-date review, Hirosh & Degani, 2018). A recent review of structural and

functional differences in bilinguals relative to monolinguals highlighted several potential

avenues for future work (Hayakawa & Marian, 2019). One potential explanation for a general

word learning advantage in bilinguals may come from examining differences in pre-lexical

processes and the underpinning structures relative to monolinguals. There is a large body of

research that shows bilingual infants are more sensitive to non-native contrasts compared to

monolinguals (e.g., Byers-Heinlein & Fennell, 2014). A smaller body of research has shown

similar findings amongst adults (Skoe et al., 2017) and that bilingual adults are better able to

learn non-native contrasts than monolinguals (Antoniou et al., 2015). Recently, Zhao and

Kuhl (2018) demonstrated that this effect may be driven by differences in auditory brainstem responses as a consequence of broader linguistic experience. Zhao and Kuhl showed that bilinguals were better at discriminating between bilabial stop consonants /ba/ and /pa/ that varied in their voice-onset times, than monolinguals. Subsequent EEG and MEG recording of auditory brainstem responses revealed longer latency of brainstem responses to voice onset times in bilinguals and longer brainstem response latencies were positively correlated with sensitivity in detecting target consonants. Other studies have demonstrated an advantage in low-level auditory processing of the fundamental frequency of speech sounds, which is robust across linguistic contexts (Skoe et al., 2017). These findings demonstrate that bilingual language experience is associated with increased efficiency of speech processing at the very earliest stages of auditory and phonetic processing. These more fundamental differences in auditory and phonetic processing may explain the advantage in novel word learning that thus far cannot be convincingly accounted for by differences in language learning context (immersion vs. classroom; Kaushanskaya & Marian, 2009b; Kaushanskaya, Yoo, & Van Hecke, 2013; van Hell & Mahn, 1997), phonological working memory ability (Kaushanskaya, 2012; Nair et al., 2016) or cognitive control (Bartolotti et al., 2011; Bartolotti & Marian, 2012). Consideration of more fundamental differences in auditory/phonetic perception and their underpinning structures needs to feature more heavily in studies investigating the bilingual word learning advantage, alongside examination of contextual and cognitive factors associated with language experience that may mediate these changes.

6.5.6 Limitations and Future Directions

In the present study, Dutch was chosen as the to-be-learned language because of its relative similarity to English to a) facilitate selection of phonological cognates and b) to isolate the direct influence of typologically distant Welsh on appraisal of the novel words. This way we could examine the effects of language experience in as neutral a manner as

possible. Some studies have suggested that the word learning advantage for bilinguals may be specific to less phonologically similar targets (Kaushanskaya et al., 2013; Papagno & Vallar, 1995). The similarity in the phonological inventory of Dutch to English in the present study may have masked a bilingual advantage in accuracy. In a recent study, Schepens et al. (2016) examined the influence of linguistic distance on proficiency of Dutch (as L2 or L3) measured by the state examination of Dutch in 39,300 people with a broad range of L1, L2 and L1-L2 combinations. Schepens et al. (2016) showed that bilinguals with any combination of languages outperformed monolinguals in Dutch proficiency scores and in addition showed strong influences of linguistic distance between Dutch and the L1 and L2 of bilinguals, with better outcomes for participants whose languages were more closely related to Dutch. Direct comparisons of the word learning advantage for typologically close and distant languages in the same groups of participants would be needed to test this question directly.

A further limitation of the present study was the choice of follow-up task. Backward translation too difficult for our participants who had had very limited exposure to a novel language. This led to considerable variability which may have masked an advantage in access to the novel forms for bilinguals. Backward translation was chosen to avoid ceiling effects for targets with high phonological similarity to their English translation that would have been likely to occur in translation recognition tasks. Utilising tasks or techniques that track subtler differences in lexical access following a period of learning would be beneficial in future studies. For example, Bartolotti and Marian (2012) measured the extent of competition experienced from phonological competitors presented alongside target pictures during a word recognition tasks. Despite training monolinguals and bilinguals to the same criterion on novel words, bilinguals showed better management of lexical competition in measure of eye and mouse tracking. At earlier stages of learning, these tools could be invaluable to examining advantages in lexical access.

6.5.7 Conclusion

The present study demonstrated that phonological wordform similarity is a robust cue to meaning for learners encountering a novel language for the first time. Proficient Welsh-English bilinguals showed a generalised advantage in decision times during associative learning of novel Dutch targets but this was not observed in accuracy during learning or backward translation. Phonological working memory promoted better discrimination between targets and foils and language switching tendencies may moderate the size of the advantage to some degree. However, neither of these factors can explain the overall word learning advantage in the present study. In attempting to explain the origins of the bilingual advantage in word learning, future studies need to look to more fundamental elements of auditory/phonetic processing altered by language experience in conjunction with moderating effects of contextual and language-specific factors. Adopting associative learning tasks and subtler assessment of lexical access following initial exposure would provide greater insight into the effects of language experience on learning and access of novel linguistic stimuli.

Running head: TDCS & WORD LEARNING

Chapter 7: Task and Participant-Dependent Effects of tDCS on Foreign Vocabulary Learning

and Backward Translation

7.1 Abstract

Several studies have shown that anodal transcranial direct current stimulation (tDCS) applied over left temporal-parietal regions can facilitate learning and retention of novel pseudowords. The present study extended previous work and tested for a facilitative effect of tDCS on associative learning of a real foreign language. The study further tested whether phonological similarity of target stimuli and participants' phonological working memory moderated expected tDCS effects. Thirty-two participants took part in a single-blind, cross-over design, where they received 1mA sham and anodal tDCS on two consecutive days. Stimulation was applied to the left temporal parietal region during completion of an associative learning task. Retention of vocabulary was assessed through backward translation at three timepoints: immediately, the day after, and a week following learning. The study replicated previous work that showed strong facilitation effects of phonological similarity on word learning and translation performance, as well as a word learning advantage for participants with better phonological working memory abilities. tDCS effects were subtle and differentially moderated by these two factors. For participants with higher phonological working memory, tDCS slowed the improvement in correct rejection times for foils with low levels of phonological similarity to English. In translation however, tDCS facilitated the longer-term maintenance of representations of the highest similarity targets, for participants with lower phonological working memory. These data indicate that tDCS may be maximally effective where some learning has taken place but where floor and ceiling effects are avoided, consistent with stochastic resonance and network-state dependency accounts.

7.2 Introduction

Several studies have demonstrated anodal transcranial direct current stimulation (tDCS) applied over the left temporal-parietal region can improve learning and consolidation of novel pseudowords in healthy adults. The aim of the present study was to extend this literature to test whether anodal tDCS applied over the same region could produce a similar effect for participants learning real foreign language words. Previous studies have not examined the effects of participant or stimulus-level characteristics in moderating the effects of tDCS on word learning. Understanding the factors that interact with non-invasive brain stimulation is critical to inform future development and application of the technology. To further this end, the present study tested for moderating effects of phonological similarity of the target stimuli, and participants' phonological working abilities, two key determinants of word learning success.

Delivery of weak, direct current into the brain is thought to modify task-related activity by inducing shifts in relative polarisation of the resting membrane potential for groups of neurons in the path of current flow (Stagg & Nitsche, 2011). Over a sustained period of tens of minutes, tDCS can produce after effects that outlast the period of stimulation for up to an hour, facilitating long-term potentiation or depression, depending on the polarity of current delivered into a task-critical region (Stagg & Nitsche, 2011). However, it has become increasingly apparent over recent years that polarity-specific accounts of tDCS effects are too simplistic and that the direction, duration and size of tDCS effects are affected by a variety of protocol, participant and task characteristics (Jacobson et al., 2012; Krause & Cohen Kadosh, 2014; Berryhill et al., 2014; Batzikadze et al., 2013). More recent perspectives on the nature of the effects of tDCS suggest that the activation state of the network is paramount in determining the direction and size of the behavioural modification induced by stimulation (Fertonani & Miniussi, 2017; Miniussi et al., 2013). The state of the

network during a stimulation session is likely to be influenced by a variety of factors,

including the relative difficulty of the task and participants' baseline ability/characteristics

(Benwell et al., 2015; M E Berryhill & Jones, 2012)), as well as more general differences in

brain morphology and protocol characteristics (Krause & Cohen Kadosh, 2014). Miniussi et

al. (2013) also propose that the effects of tDCS can be characterised within the framework of

stochastic resonance, such that adding a small amount of additional background noise, may

boost both the target signal and some of the noise correlated with it, facilitating or decreasing

performance. The effects of tDCS are likely to impact neurons that are close to threshold and

where signal-to-noise ratios are more moderate. Learning studies that result in a transition

from low to more moderate signal-to-noise ratios within an active network may be

particularly sensitive to the effects of tDCS under this account.

The focus of the present study is on the effects of tDCS for facilitating novel word

learning. A series of studies have demonstrated a relatively consistent facilitative effect on

pseudoword learning, during and following the application of anodal tDCS over left

temporoparietal cortex. Flöel, Rösser, Michka, Knecht and Breitenstein (2008) showed

improved accuracy in a well-established associative learning paradigm under anodal

stimulation relative to sham and cathodal stimulation. In this paradigm, learning is

accomplished through exposure to consistent pairs of pseudowords and familiar object

pictures (e.g., Breitenstein et al., 2005; Breitenstein & Knecht, 2002). The advantage for

anodal stimulation transferred into a translation decision task administered immediately after

stimulation but the advantage for anodal tDCS was not present at follow-up a week later.

Fiori and colleagues (2011) presented 10 participants with 20 pseudowords and

corresponding object pictures, followed by a recognition task to probe learning. In this study,

20 minutes of 1mA tDCS was delivered during spoken retrieval of the novel names assigned

to the objects. Anodal tDCS applied over left temporal-parietal regions resulted in faster

mean response times compared to anodal tDCS applied over the right occipital-parietal region and sham. Savill et al. (2015) examined the effects of 1.5mA applied for 15 minutes over the same temporoparietal region during an explicit learning task. These authors tested the phonological coherence of learned pseudowords, the day after stimulation, testing medium term effects on consolidation, and ruling out residual activation immediately following stimulation. Participants completed an immediate serial recall task and showed improved whole word and partial production of pseudowords learned under anodal relative to sham stimulation. Finally, Meinzer et al. (2014) presented evidence from the first multi-session language learning study in two independent groups of participants who received either sham or anodal stimulation over five days, applied concurrently with a visual word learning task. Anodal tDCS resulted in enhanced learning and consolidation of novel pseudowords paired with both familiar and unfamiliar object pictures. The improvement in learning under anodal tDCS was greatest for pseudowords paired with unfamiliar objects but was substantially greater than sham for both sets of stimuli.

In the studies discussed above, stimulation protocols were generally consistent utilising a current density of 0.028 mA/cm^2 with the anode centred over the left temporoparietal region, plus a right forehead reference site. However, all of the studies described above exclusively examined the effects of tDCS on learning and retention of native-language derived pseudowords, which may reflect new word learning in a known language but may not generalise to learning of unfamiliar foreign language words.

Pseudowords are ideal for control of various stimulus characteristics and ensure that participants can draw on very little explicit top-down lexical knowledge to influence their performance. With carefully designed pseudowords, somewhat 'pure' effects of learning can be examined, although learning these words are advantaged over highly dissimilar, foreign language words by the fact that each pseudoword conforms to the phonotactics of the known

language, a factor that facilitates word learning (Papagno, Valentine, & Baddeley, 1991;

Service & Kohonen, 1995; Stamer & Vitevitch, 2012; Storkel, Armbrüster, & Hogan, 2006;

Vitevitch & Luce, 2016; see Kaushanskaya & Marian, 2009b for a clever solution).

An adult's lexical knowledge is of paramount importance in learning new words in an

unfamiliar language and the ability to exploit familiarity and similarity is paramount for

success, especially at the very early stages of learning (Berthele, 2011; Susanne Elizabeth

Carroll, 2012; Ecke & Hall, 2014; Hall, 2002; Odlin, 2012; Otwinowska & Szewczyk, 2017;

Ringbom, 1992, 2007; van Hell & Tanner, 2012; Vanhove & Berthele, 2015). There is little

reason to expect that the general processes and networks that underpin pseudoword learning

and foreign language learning differ in any substantive way (Lindsay & Gaskell, 2010;

Ullman, 2016). However, the interaction between participants' top-down knowledge and the

characteristics of novel words is likely to moderate activity within this network and thus,

moderate the effects of tDCS.

Learning a new word fundamentally relies upon consistent mapping between form

and meaning. This process is underpinned by the interplay between speech processing and

memory systems for success. The complementary learning systems account of language

learning (M. H. Davis & Gaskell, 2009) proposes a framework that integrates the Cohort

Model of Speech Comprehension (Gaskell & Marslen-Wilson, 1997; Marslen-Wilson, 1987)

with the complementary learning systems account of memory (McClelland et al., 1995).

Classical speech comprehension models, like the Cohort model, propose three stages for

access to meaning from spoken words: 1) early processing of the acoustic signal, 2)

activation of phonological wordforms in the lexicon, and 3) subsequent activation of related

meaning(s) (Weber & Scharenborg, 2012). Under the dual-stream model (Hickok & Poeppel,

2007, 2015), acoustic and phonemic processing occurs bilaterally in primary and secondary

auditory cortex and phonemic and syllable-level representations begin to activate stored

representations in the phonological lexicon. Posterior superior temporal sulci and inferior parietal lobes are thought to reflect storage and maintenance of phonological lexical forms (Buchsbaum et al., 2001; Graves et al., 2008; Leff et al., 2009; Okada & Hickok, 2006; Prabhakaran et al., 2006). Phonological form information is then integrated with lexical semantic representations fed back from posterior middle temporal gyri and fusiform gyrus, although conceptual representations in general are thought to be broadly distributed.

When we encounter any word, novel or known, a representation for that specific event is created in episodic memory for later use. The hippocampus and medial temporal lobe structures are critical for learning new information and support the creation, retrieval and consolidation of episodic memories (Squire & Wixted, 2011; Ullman, 2016). On encountering a novel wordform, a representation must be created for later access and needs to be bound to meaning in some way to be of functional use. A process of fast mapping is thought to facilitate rapid acquisition of novel words and their meaning in both children and adults (Coutanche & Thompson-Schill, 2014; Mayor & Plunkett, 2010; Trueswell et al., 2013; Yu & Smith, 2007). Co-occurrence between a meaningful referent, like a familiar object, and a new word will facilitate form-meaning mappings and strengthened by further exposure.

Strong evidence for the role of the hippocampus in establishing form-meaning mappings for novel words comes from a study by Breitenstein et al. (2005). In this study, novel pseudoword vocabulary was acquired via associative learning of consistent picture-word pairs. Greater activation in the hippocampus at the outset of the task and a shallower decline in activity was associated with greater learning success during and following the five blocks of learning trials. Concurrent increases in activation in inferior parietal regions were also associated with better learning of novel pseudowords. Activation patterns to inconsistent pairs were not moderated to a substantial degree. In subsequent studies, this research group

have demonstrated rapid integration of novel forms into the existing lexicon after periods of exposure lasting 20 minutes. For example, Dobel et al. (2009) have shown word-like N400m responses during a semantic decision task to consistent word-picture pairs, following a 20-minute learning period, indexing rapid semantic integration.

The strength of the initial episodic trace for a novel word is likely to be enhanced through access to top-down lexical knowledge (Lindsay & Gaskell, 2010). One pertinent factor for learning novel words is the phonological similarity of the target word to known words in the lexicon (Ringbom, 2007; Vitevitch & Luce, 2016). Target wordforms with similar phonotactic structure to known words and dense phonological neighbourhoods facilitate word learning, because of partial activation of stored representations (Storkel et al., 2006). Moreover, whole wordform similarity can be a particularly salient cue (Berthele, 2011; Bradley et al., 2013; De Groot & Keijzer, 2000; Dijkstra et al., 2010; Ellis & Beaton, 1993a; Hall, 2002; Lotto & De Groot, 1998; Otwinowska & Szewczyk, 2017; G. Raboyeau et al., 2010; Ringbom, 2007; van Hell & Tanner, 2012; Vanhove & Berthele, 2015). For example, the Dutch word /boek/ would produce cascaded activation to the English word /book/, its neighbours (i.e., boom, boot, brook), and their associated meanings. In this case, the high phonological similarity between the Dutch and English words for book, indicates a cognate form that would facilitate access to the meaning, further strengthened by co-occurrence with the relevant referent. In this case, wordform representations for the novel Dutch form can be adapted from the template for the known word in English. For non cognates, or novel word forms that share little phonological information with known words, then a completely new wordform representation must be created in episodic memory (Lindsay & Gaskell, 2010). This trace and its mapping with meaning is substantially weaker than for more phonologically similar forms and would require much more exposure before successful integration into the existing lexicon. Noncognates from a novel foreign language

likely reflect a more difficult learning task than for native-language derived pseudowords that include strong phonotactic cues.

Fundamentally, the complementary systems account and models of speech comprehension more generally, presuppose a continuum of phonological similarity. There are no hard borders in phonological representation and yet word learning studies that have examined the effects of 'cognateness' simply test cognates and noncognates in broad categories, ignoring the subtle difference between stimuli (Bradley et al., 2013; De Groot & Keijzer, 2000; Lotto & De Groot, 1998; G. Raboyeau et al., 2010). In the context of the present study, variation in phonological form similarity is expected to produce different levels of activation within the network that underpins novel word learning. As phonological wordform similarity increases, the strength of competition and cascaded co-activation within the network is likely to increase. Strong cognate forms, like /boek/, would result in a relatively high signal-to-noise ratio, increasing activation in speech comprehension networks and providing a strong anchoring stimulus for the episodic trace on first and subsequent exposure. The relative activation profile and strength of the fast mapping response would decrease with decreasing levels of phonological similarity. In chapter 5, strong evidence for a phonological similarity bias was found during learning, with much shallower learning curves for targets with the greatest similarity to known words. As well as trial-by-trial activation, long-run activation profiles will transition from lower to more moderate signal-to-noise states for targets with lower phonological similarity that may interact with tDCS in an important manner. From this perspective, foreign language learning and manipulation of phonological form similarity can be seen as a formal test of the network-state dependency account of tDCS.

One additional consideration for a study of word learning is that adults differ substantially in their relative success. One of the fundamental skills that is thought to

underpin an individual's ability to learn new words is their phonological working memory

ability (Gathercole, 2006; Gathercole & Baddeley, 1993, 2014; Gupta & Tisdale, 2009a;

Majerus et al., 2008). To date, no tDCS studies have examined the influence of this

moderator on participants' response to stimulation during vocabulary learning. Greater

baseline levels of phonological working memory and better maintenance or control of the

episodic mapping of novel words and their pictures will likely result in better coherence in

the language learning network. How tDCS might interact with different levels of

phonological working memory ability is an open question in need of study.

The aim of the present study was to extend previous findings that tDCS can facilitate

learning of novel pseudowords to the study of real foreign language vocabulary. Following

recent proposals that the network-state of an individual during a task is likely to be

instrumental in determining the final tDCS effect, we examined two factors critical to

successful foreign language vocabulary acquisition; the phonological similarity of the target

and the phonological working memory ability of the participants. To date, only one study has

examined the effects of electrical stimulation during real foreign language learning

(Pasqualotto et al., 2015). Pasqualotto and colleagues (2015) applied transcranial random

noise stimulation (tRNS) to bilateral superior parietal regions or dorsolateral prefrontal

cortex. This form of stimulation acts through delivery of randomly fluctuating current that

produces effects akin to anodal tDCS, concurrently at both electrode positions (e.g., Paulus,

2011). In their study, Pasqualotto et al. (2015) employed a visual paired-associate word

learning paradigm with a drop-out protocol, such that subsequent blocks included fewer

learning pairs. Active tRNS resulted in better retention of Swahili noncognate vocabulary

one-week following learning relative to sham, but only following the application of

stimulation to superior parietal cortex but not dorsolateral prefrontal cortex. However,

justification for stimulation at these two sites was weak and incongruent with previous

studies which have focused on stimulating temporal-parietal regions. Moreover, the use of a drop-out paradigm makes it very difficult to establish how exposure and subsequent learning interacts with stimulation.

In the present study, we adapted the well-established associative learning paradigm created by Breitenstein and colleagues (e.g., Breitenstein et al., 2005) and utilised in the first tDCS study on pseudoword learning by Flöel et al. (2008).Furthermore, a tDCS protocol consistent with previous tDCS studies was adopted for the present study, namely a 1mA current with a current density of 0.028 mA/cm^2 with the anode centred over left temporal parietal cortex plus a forehead reference. Anodal tDCS was expected to produce an overall improvement in vocabulary learning and translation performance compared to sham. Given mixed evidence from previous studies, we expected that gains in learning could be present during learning or emerge at any timepoint where translation performance was assessed – immediate, day after or a week later. Assessment of consolidation at multiple timepoints may aid in determining when and how tDCS affects acquisition and/or consolidation of new words (for discussion, Au, Karsten, Buschkuehl, & Jaeggi, 2017). Fertonani and Miniussi (2017) propose that tDCS may optimally affect learning as the network state transitions from low coherence through to moderate/high coherence state, strengthening LTP and thus learning. The effects of tDCS could emerge at the whole task level – a general improvement in vocabulary learning – or be specific to item sets within a vocabulary. To examine this, the phonological similarity between the to-be-learned Dutch translations and their English counterparts was manipulated, representing a within-task state-dependent manipulation. Under the network-state dependency account, it could be expected that because of the increased difficulty of learning less phonologically similar words that tDCS may specifically facilitate learning of these items. Furthermore, a participant's propensity for learning new words may also interact with tDCS. The present study tested for moderating effects of

phonological working memory. It is possible that tDCS may show a stronger facilitative effect for participants with lower phonological working memory. As these participants are at a disadvantage in maintaining phonological representations in the short term, increased activation in the temporoparietal region, and throughout the network, during encoding, might produce a stronger effect on learning and/or consolidation. For participants with higher phonological working memory, tDCS could have a weaker effect, no effect, and could even impair performance, if the signal-to-noise is already optimal but subsequently perturbed by increased noise. The interaction between phonological memory, phonological similarity and learning may be quite complex and is an open question in need of investigation.

7.3. Method

7.3.1 Participants

Thirty-two monolingual English speakers were recruited from the student population at Bangor University and the surrounding area and were compensated with course credits and/or £15 for their time. Participants were included in the study if they were over the age of 18, a monolingual speaker of English (i.e., no continued use of a second language after school/college), with no/little knowledge of Dutch (below 3 on scale from 0 = No knowledge to 9 = Native/Native-like), normal or corrected-to-normal vision and hearing, and no history of language difficulties. Participants were screened for contraindications for transcranial electrical stimulation prior to taking part in the study. We administered an in-house questionnaire that recorded information on demographics, language background, proficiency in a foreign language and knowledge of Dutch. Demographic and background information are presented in Table 7.1. Ethical approval was granted by the School of Psychology research ethics committee at Bangor University (2015-15577).

Table 7.1.

Demographic and Background Information

Age M (SD)	Sex (M/F)	Waterloo Handedness Scale M (SD)	CTOPP-2 Phonological Memory Subscale[a] M (SD)	BPVS[a] M (SD)	Dutch Knowledge[b] *Median* (*Min, Max*)	At least one language learned	
21.19 (5.63)	7 / 25	22.72 (6.21)	95.28 (9.79)	109.66 (8.74)	0 (0, 2)	KS3	75%
						KS4	88%
						KS5	16%

Notes: a = Scaled scores; b = 0-9 scale (0 = No knowledge at all; 9 = Native/Native-like speaker); BPVS = British Picture Vocabulary Scale; CTOPP-2 = Comprehensive Test of Phonological Processing, second edition

7.3.2 Background Measures

Participants completed the phonological memory subtests (Nonword Repetition and Memory for Digits) from the Comprehensive Test of Phonological Processing – Second Edition (CTOPP-2; Wagner, Torgesen, Rashotte & Pearson, 2013), and the British Picture Vocabulary Test – III (BPVS-III; Dunn, Dunn, Styles & Sewell, 2009). The basal set for the BPVS for all participants was set 10 (age 14+) and the test was administered according to published testing procedures but administered through E-Prime 2.0 using pre-recorded stimuli. Scaled scores were calculated for all tests and subtests.

7.3.3 General Procedure

Participants took part in four experimental sessions (see Figure 7.1 for diagrammatic overview). Sessions one to three were completed on consecutive days (approx. 60mins each) and the fourth, follow-up session a week later (15mins). In the first session, participants were given detailed information about the experimental sessions and what to expect when undergoing tDCS, before giving informed consent. Any participants who reported contraindications for tDCS were not eligible to take part and were not entered into the study. In the remainder of the first session, participants completed the first, of two learning tasks, paired with either active or sham stimulation. Immediately following the end of the task participants completed part A of the stimulation tolerability questionnaire (Fertonani et al.,

2015), followed by a backward translation task. At the beginning of day two, participants

completed a translation task for the second time, associated with the stimulus list they had

learned on day one. On the same day, they then learned a second vocabulary list paired with

the remaining stimulation type, followed by part A of the tolerability questionnaire for that

session, and a backward translation task. In the third session, participants completed the

second translation task for the list learned on day two, part B of the tolerability questionnaire,

plus the background tests and demographic questionnaire. Participants returned to the lab one

week after the third session and completed the translation tasks for List A and B before being

debriefed. Stimulation and list order were fully counterbalanced across participants and

sessions.
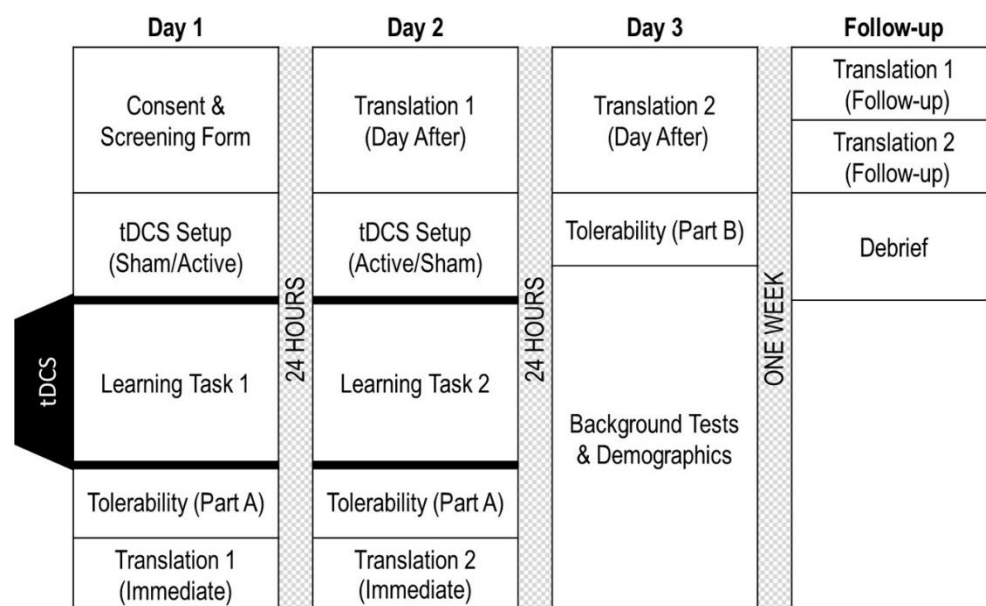
Figure 7.1. General procedure outline.

7.3.4 Tasks and Stimuli

The tasks and stimuli were identical to those employed in Chapter 6. See Figure 7.2

for diagrammatic overview.

A: Learning Task
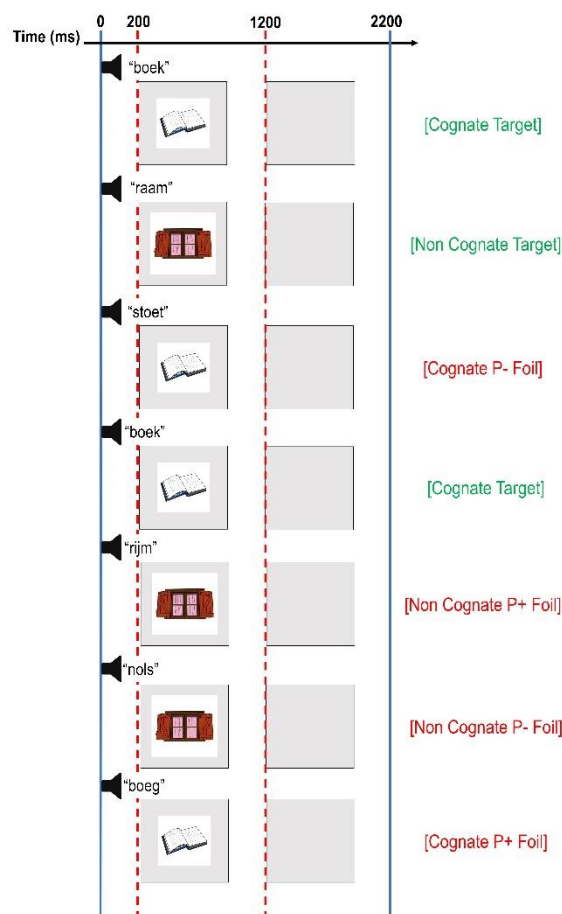
B: Translation
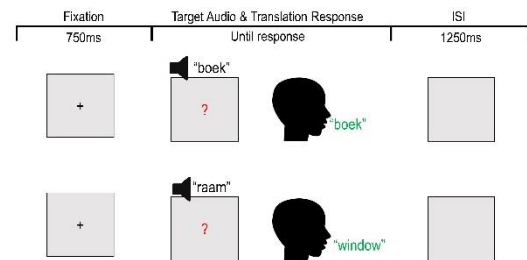
C: COMETS2
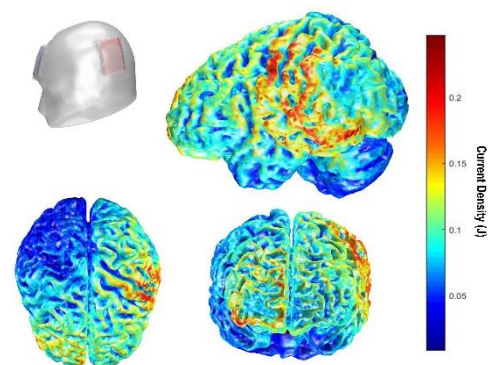
Figure 7.2. Example trials and structure for the learning task (A) and translation task (B), and COMETS2 (Lee et al., 2017) current density estimations for the tDCS montage (C).

7.3.5 Transcranial Direct Current Stimulation

Transcranial direct current stimulation was delivered with a DC Stimulator-Plus (Neuroconn, Rogue Resolutions, Cardiff), at 1mA, via two 35cm^2 electrodes (0.029 mA/cm^2), inserted into sponge pads moistened with 0.75% saline solution. In accordance with previous tDCS studies (Fiori et al., 2011; Flöel et al., 2008; Marcus Meinzer et al., 2014; Savill et al., 2015), the anode electrode was placed over area CP5, according to the EEG 10-10 system, which critically overlies the posterior superior temporal (pSTG) and supramarginal gyri (SMG; Jurcak, Tsuzuki, & Dan, 2007). The reference electrode was applied to the right supraorbital region. Figure 7.2c shows the predicted current density

within the cortex generated using the COMETS2 tool (Lee et al., 2017). The COMETS2

simulations show diffuse current flow from the left hemisphere through to right frontopolar

cortex but maximal concentration of current is centred over pSTG and SMG in the left

hemisphere and superior to inferior frontopolar cortex, consistent with electrode placement.

Electrodes were held on the scalp with elasticated, velcro straps and impedance was

established at <5kΩ before starting stimulation. Stimulation was delivered concurrently with

task performance. Participants were reminded of the task instructions during the 15s ramp on

and asked to begin the task. Stimulation continued for 20mins in active conditions or 30s in

sham conditions, before ramping down over 15s.

7.3.6 tES Tolerability Questionnaire

The tES tolerability questionnaire created by Fertonani et al. (2015) was administered

to all participants (Part A: Day 1 & 2; Part B on Day 3). Blinding was successful, as correct

identification of both stimulation types was significantly less than expected by chance (9/32;

$\chi^2(1) = 6.13$, $p = .02$). Differences in intensity between stimulation sessions were assessed

with Wilcoxon Signed Ranks tests and descriptive statistics for nine after effects are

presented in Table 7.2. Itching was significantly more intense ($V = 138.50$, $p < .002$) and

overall discomfort (summed intensity sensations) was higher on average in active sessions (V

$= 183$, $p < .07$). Intensity ratings for other after effects were not significantly different

between sessions. Most participants reported sensations at the beginning of the stimulation

period (Sham: 87.50%, Active: 87.50%), but perception of sensations lasted until the end of

the 20min period more frequently in active (43.75%) compared to sham sessions (15.63%).

However, perceived 'discomfort' did not affect performance 'at all' or 'only slightly' in most

stimulation sessions (62/64, 96.88%).

Table 7.2.

Mean (Standard Deviation), Median and Incidence (% Sample) of Tolerability Questionnaire

Responses.

	Sham			Active		
	Mean (*SD*)	Median	Incidence	Mean (*SD*)	Median	Incidence
Itching	**1.16 (0.81)**	1	88%	**1.75 (0.88)**[‡]	2	97%
Pain	0.31 (0.82)	0	19%	0.12 (0.34)	0	12%
Burning	0.34 (0.83)	0	22%	0.41 (0.67)	0	34%
Heat	0.66 (0.75)	1	53%	0.72 (0.73)	1	59%
Pinching	0.16 (0.37)	0	16%	0.22 (0.42)	0	22%
Iron.Taste	-	-	-	-	-	-
Fatigue	0.62 (0.71)	0.5	50%	0.56 (0.67)	0	47%
Discomfort	**3.25 (2.93)**	3	94%	**3.78 (2.18)**[†]	3	97%

Note: Wilcoxon signed ranks test used to determine statistical differences.. ‡ = $p < .002$; † = $p - .067$

7.3.7 Design and Data Analysis

This study had a complete within-subjects design. Two dependent variables were

collected and analysed for the learning task: the proportion of match responses and response

latencies, collected from the onset of the object picture. Previous studies examining learning

in a task such as this have focused purely on hits – correctly identified 'match' responses –

which potentially conflates accurate responding with a biased response strategy. On each

trial, participants had to make a two-forced choice decision between a match and non-match

response and therefore true learning should be characterised by a response strategy that not

only maximises hits on target, match trials, but also minimises false alarms on non-match,

foil trials. In line with a signal detection approach we consider discrimination performance,

or rather the relative difference in the proportion of hits and false alarms to be indicative of

learning. Moreover, previous studies utilising a paradigm such as this have dismissed

response latency data as purely a marker of arousal rather than indicative of a learning

response. Under a signal detection framework, response latencies may provide subtler insight

into the nature of the learning process, when other moderators are present. In analyses of response latencies, we included data for hits and correct rejections, as the parallel to discrimination performance. Evidence of greater learning would be observed if response latencies decreased to both hits and correct rejections as exposure increase. Response latencies to false alarms are not appropriate as response on these trials reflect an error in responding, rather than affirmation of learning. In parsimonious mixed effects models fit to the learning task data, fixed effects of Trial Type (Target, Foil), Stimulation Type (Sham, Active), Block (1-5) and Phonological Similarity Band 1: [0, 0.1], Band 2, [0.1-0.3], Band 3: [0.3-0.5], Band 4: [0.5-0.8]). Moderating effects of other key fixed factors provide insight into how over blocks and as function language status and phonological similarity.

In the translation task, accuracy of the translation response was recorded (0 = incorrect, 1 = correct). Fixed effects of Stimulation Type (Sham, Active), Session (Immediate, Day After, Follow-up) and Raw PNLD Bands (Band 1 – Band 4) were included as within-subject fixed effects.

7.3.7.1 Parsimonious Mixed Effects Models.

All analyses were conducted in Microsoft Open R 3.3.2 (Microsoft R Application Network, 2014), a distribution of the R software (R Core Team, 2016), optimised for multi-core processing. For implementation of mixed models under a signal detection framework see the work of Wright and colleagues (Jacobs et al., 2016; Schwartz & Wright, 2012; Wright et al., 2009, 2011; Wright & London, 2009). Parsimonious mixed effects models were conducted using maximum likelihood estimation with the lme4 1.1-12 (Bates et al., 2014) and RePsychLing 0.0.4 packages (H. Baayen et al., 2015), as outlined by Bates, Kliegl, Vasishth and Baayen (2015; see also Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). We applied a backward elimination method to the reduction of the random effects structure. The 'maximal' model included all possible two-factor interaction terms as slopes for both

Concept and Participant random effects. We did not include further higher effects because the variance of three- and four-way interactions would likely have been too small to be meaningful, and this substantially reduced computation time. A random slope was retained if a likelihood ratio test showed a significant reduction in model fit (at $p < .05$), with minimal change in AIC of at least 4 points, and the excluded slope accounted for at least 1% of variance in the random effects principal components analysis, implemented in the RePsychLing package.

Generalised linear mixed models (GLMM) with a logit link function were fit to binomial response variables for the learning task (0 = non-match, 1 = match) and the translation task (0 = incorrect, 1 = correct). Linear mixed models (LMM) were fit to response latencies to hits on Target trials and correct rejections of Foil trials only. The two-level fixed effects of Stimulation (Sham, Active) and Trial Type (Foil, Target) were centre, sum-coded (e.g., ~+0.5, ~-0.5; see Nieuwenhuis, te Grotenhuis, & Pelzer, 2017). In the learning task, the natural logarithm was applied to Block, reducing the need for a quadratic term in the model. For the translation task, Block was replaced by a categorical predictor of Session (Immediate, Day After, Follow-up). Centred backward difference contrasts were applied to the fixed effect of Session (Immediate, Day After, Follow-up), resulting in two contrasts: Immediate vs. Day After; Day After vs. Follow-up. Backward difference contrasts were applied to Phonological Similarity Band factor to compare performance for items as a function of increasing similarity, comparing one phonological similarity bin with the previous (i.e., Band 1 vs. 2; 2 vs. 3; 3 vs. 4). All main effects and interaction terms were included in the fixed effects part of the models.

Residuals were examined for uniformity with the DHARMa package (Hartig, 2016) for GLMMs and LMERConvenienceFunctions package for LMMs (Tremblay & Ransijn, 2015). We took a minimal *a priori* data trimming approach following Baayen and Milin

(2010), reducing any heteroskedasticity with appropriate transformation before excluding influential trials from LMMs using the romr.fnc function from the LMERConvenienceFunctions package. Wald approximate p-values were generated for GLMMs. The Satterthwaite degrees of freedom adjustment was applied to generate approximate p-values for LMMs, using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2016; for discussion Luke, 2017). All data presented in figures were extracted from mixed effects models using the effects package (Fox, 2003; Fox & Hong, 2009) and figures were created using ggplot2 (Wickham, 2016).

7.4 Results

7.4.1 Associative Learning

A total of 38,400 observations were collected from the learning task. Of these trials, 1194 (3.11%) were lost because participants timed-out and a further 16 trials (0.042%) were excluded because response latencies were less than 200ms, based on visual examination of raw distributions leaving a total of 37,190 trials for the GLMM analysis (96.85%). For the LMM analyses of response latencies, 25,756 trials were included because of the omission of false alarms and miss trials.

7.4.1.1 Model Fitting

For the GLMM fit to the discrimination data, the parsimonious random effects structure included a random intercept for Participants with random slopes of log(Block), Stimulation, and a Stimulation x RawPNLD interaction term. A random intercept for Concepts was included, with random slopes of log(Block) and Stimulation. Inclusion of random effects correlations substantially improved model fit ($AIC_{DIFF} = 112.03$). The residuals from the parsimonious GLMM conformed to a uniform distribution (p = .62, n = 500 iterations). The formula for the parsimonious GLMM model is presented below:

glmer(Match ~ Stimulation*log(Block)*PhonologicalSimilarity*TrialType+

   (1 + log(Block)*Stimulation | Participants) +

   (1 + log(Block) + Stimulation | Concept), family =

   binomial("logit"),…

The parsimonious random effects structure for the LMM fit to response latencies was identical to the GLMM model for accuracy, except that the random slope of Stimulation within Concepts was retained (model formula below). Random effects correlations substantially improved model fit of the LMM (AIC_{DIFF} = 54.27). However, inspection of residuals showed heteroskedasticity. Log transformation of response latencies produced the best fitting residuals, compared to untransformed and square root transformations (BoxCox λ 0.65, see Kliegl, Masson, & Richter, 2010; Cramér von-Mises[7] W^2_{RAW} = 15.35; W^2_{LOG} = 2.04; W^2_{SQRT} = 5.84; fitdistrplus, Delignette-Muller & Dutang, 2015). Using the romr.fnc (Tremblay & Ransijn, 2015) 411 trials (1.59%, trim = 2.5) were automatically identified as outliers and removal substantially improved model fit (AIC_{DIFF} = 3585.10). The LMM coefficients reported below correspond to log transformed response latencies for this reduced model.

lmer(log(RT) ~ Stimulation*log(Block)*RawPNLD*TrialType +

   (1 + log(Block) + Stimulation*RawPNLD | Participants) +

   (1 + log(Block) + Stimulation | Concept), family =

   binomial("logit"), …

7.4.1.2 Model Outcomes

Figure 7.3 shows the discrimination data and model estimates for these data are presented in Table 7.3. Estimates extracted from the parsimonious model for the response

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[7] Cramér von-Mises *T* is a one-sample goodness-of-fit test. Lower values represent better fit of data (i.e., the residuals) to an empirical distribution (i.e., normal) (Csorgo & Faraway, 1996).

latency model showed highly similar response patterns in Phonological Similarity Bands 1 and 2, and in Bands 3 and 4. For simpler interpretation of model estimates we combined the response latency data for stimuli in Bands 1 and 2, and Band 3 and 4, into Low similarity and High similarity categories, respectively. For brevity this reduced model is presented below in Figure 7.4 and Table 7.4 but summary figures and model estimates for the initial model can be found in Appendix C. Only significant effects are discussed below.

7.4.1.3 Discrimination

The proportion of Match responses was greatest to targets than to foils overall. The probability of a match response increased across blocks, and this was driven by an increasing number of hits to targets than false alarms to foils, indexing increased discrimination between consistent and inconsistently paired targets. Increasing phonological similarity between Dutch stimuli and English object names biased participants to make more match responses overall. In figure 7.3 this bias is clearly observed by the linear increase in hit and false alarm rates in block 1 as a function of phonological similarity band. The phonological similarity bias impacted learning performance, with much shallower improvements in hit rates for stimuli with higher phonological similarity values but a gradual decrease in false alarm rates, across blocks. At lower phonological similarity bands, false alarm rates remained consistently low, with a much more substantial increase in hit rates over blocks. Active stimulation did not produce any significant moderating effects on these patterns of responses relative to sham.
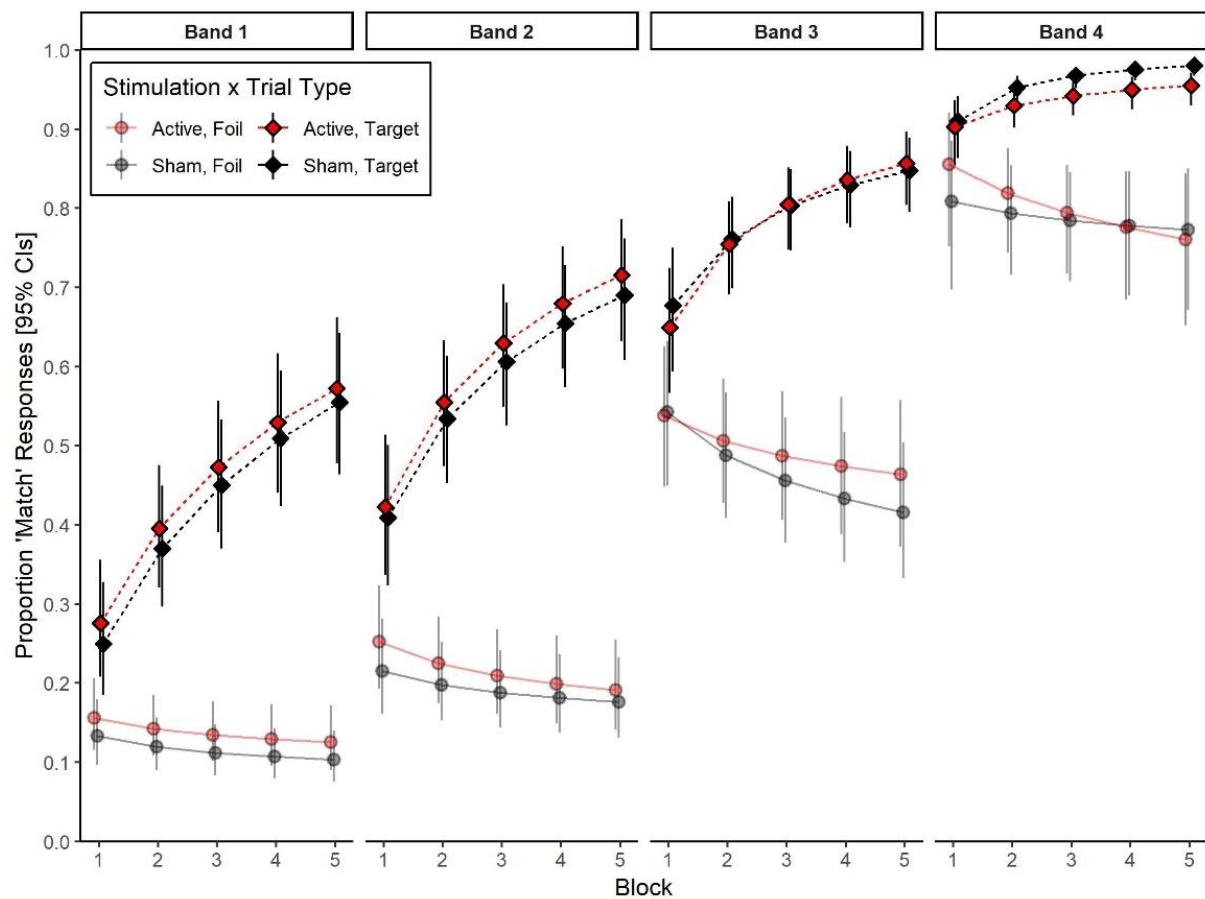
Figure 7.3. Proportion 'match' response [95% CI] in five blocks of the learning task,

separated by Trial Type, Phonological Similarity and Stimulation Type. Foils represent false

alarms.

Table 7.3.

Parsimonious GLMM Estimates for Discrimination Data from the Associative Learning Task

	Discrimination Performance			
	lnOR	*CI*	*z*	*p*
(Intercept)	-1.469	-1.82 – -1.11	-9.188	**<.001**
Stimulation (Sham, Active)	0.214	-0.09 – 0.52	1.034	.164
log(Block)	0.336	0.19 – 0.48	4.347	**<.001**
Phonological Similarity: Band 1 vs. Band 2 [PSim1]	0.701	0.52 – 0.88	8.098	**<.001**
Phonological Similarity: Band 2 vs. Band 3 [PSim2]	1.880	1.64 – 2.12	21.726	**<.001**
Phonological Similarity: Band 3 vs. Band 4 [PSim3]	3.398	3.01 – 3.78	23.556	**<.001**
Trial Type (Foil, Target)	0.781	0.58 – 0.99	7.323	**<.001**
Stimulation:log(Block)	-0.023	-0.25 – 0.21	-0.069	.846
Stimulation:PSim1	-0.083	-0.36 – 0.20	-0.196	.560
Stimulation:PSim2	-0.261	-0.55 – 0.02	-1.584	.073
Stimulation:PSim3	0.062	-0.45 – 0.57	-0.123	.811
log(Block):PSim1	-0.054	-0.19 – 0.08	-0.561	.426
log(Block):PSim2	-0.130	-0.27 – 0.01	-1.526	.069
log(Block):PSim3	-0.093	-0.34 – 0.15	-0.592	.454
Stimulation:Trial Type	-0.056	-0.44 – 0.32	-0.259	.774
log(Block):Trial Type	1.003	0.83 – 1.18	10.834	**<.001**
PSim1:Trial Type	0.078	-0.21 – 0.37	0.685	.599
PSim2:Trial Type	-0.283	-0.57 – 0.00	-1.612	**.050**
PSim3:Trial Type	-0.124	-0.63 – 0.39	-0.328	.634
Stimulation:log(Block):PSim1	0.007	-0.23 – 0.24	-0.048	.952
Stimulation:log(Block):PSim2	0.136	-0.10 – 0.37	1.117	.264
Stimulation:log(Block):PSim3	-0.402	-0.85 – 0.04	-1.576	.076
Stimulation:log(Block):Trial Type	-0.070	-0.40 – 0.26	-0.382	.679
Stimulation:PSim1:Trial Type	-0.114	-0.65 – 0.42	-0.382	.676
Stimulation:PSim2:Trial Type	-0.036	-0.57 – 0.50	-0.203	.894
Stimulation:PSim3:Trial Type	-0.393	-1.37 – 0.59	-0.735	.433
log(Block):PSim1:Trial Type	-0.070	-0.32 – 0.18	-0.267	.587
log(Block):PSim2:Trial Type	-0.092	-0.34 – 0.16	-0.388	.472
log(Block):PSim3:Trial Type	0.002	-0.46 – 0.46	0.174	.994
Stimulation:log(Block):PSim1:Trial Type	0.179	-0.28 – 0.64	0.733	.447
Stimulation:log(Block):PSim2:Trial Type	0.055	-0.41 – 0.52	0.226	.818
Stimulation:log(Block):PSIM3:Trial Type	-0.082	-0.96 – 0.79	-0.366	.854

Table 7.3 continued.

Random Parts	
$\tau_{00, Concepts}$	1.124
$\tau_{00, Participants}$	2.328
ρ_{01}	-0.628
$N_{Concepts}$	60
$N_{Participants}$	32
$ICC_{Concepts}$	0.167
$ICC_{Participants}$	0.345
Observations	37190
Tjur's D	0.392
AIC	35539.402

7.4.1.4 Response Latencies

Figure 7.4 shows the response latency data to hits on targets trials and correct rejection of foil trials. Response latencies decreased substantially from blocks 1 to 5, but responses to targets were faster than responses to foils, overall. Response latencies were faster from the outset for stimuli in the higher phonological similarity category and responses to these items showed the steepest decrease in RTs over blocks. Responses to stimuli in the higher phonological similarity category showed a steeper decline to targets compared to foils but slopes to targets and foils were similar overall in the low similarity category. Examining these effects in combination with stimulation, revealed a weak four-way interaction that showed differential effects of active and sham stimulation on the difference in RT decline over blocks between target and foil trials, but only for the low similarity stimuli. The interaction was broken down into two analyses examining the Stimulation x log(Block) x Trial Type interaction separately for low and high phonological categories (see Table 7.4 for coefficients). The three-way interaction was significant only for the less phonologically similar targets. This interaction was driven by a divergent pattern in the slopes to targets and foils for the low phonological similarity stimuli. In Figure 7.4, the response latencies reduction for low similarity targets and foils was very similar, whereas under active

stimulation the response latency reduction to foils was less steep relative to Figure 7.4 shows that for these stimuli, the reduction in response latencies to foils was less steep relative to targets, although the slope to low similarity targets was similar compared to sham. For high similarity stimuli, there was little difference in the relative slopes to targets and foils between stimulation sessions.

Table 7.4

LMM Coefficients for Log-Transformed Response Latencies

	B	95% CI	t	p
(Intercept)	6.507	6.47 – 6.54	356.40	**<.001**
Stimulation (Sham, Active)	-0.004	-0.03 – 0.02	-0.34	.738
log(Block)	-0.056	-0.07 – -0.04	-8.39	**<.001**
Phonological Similarity (Low, High) [PSim]	0.052	0.04 – 0.06	9.25	**<.001**
Trial Type (Foil, Target)	-0.037	-0.05 – -0.03	-5.60	**<.001**
Stimulation:log(Block)	-0.004	-0.02 – 0.01	-0.40	.688
Stimulation:PSim	-0.01	-0.03 – 0.01	-0.91	.363
log(Block):PSim	-0.005	-0.01 – 0.00	-1.12	.263
Stimulation:Trial Type	-0.004	-0.03 – 0.02	-0.32	.751
log(Block):Trial Type	-0.022	-0.03 – -0.01	-3.99	**<.001**
PSim:Trial Type	0.104	0.08 – 0.12	9.76	**<.001**
Stimulation:log(Block):PSim	0.01	-0.01 – 0.03	1.09	.278
Stimulation:log(Block):Trial Type	-0.001	-0.02 – 0.02	-0.06	.952
Stimulation:PSim:Trial Type	0.046	0.01 – 0.09	2.23	**.026**
log(Block):PSim:Trial Type	-0.004	-0.02 – 0.01	-0.46	.644
Stimulation:log(Block):PSim:Trial Type	-0.046	-0.08 – -0.01	-2.60	**.009**
Random Parts				
σ^2				0.025
τ_{00}, Concept				0.004
τ_{00}, Participant				0.02
ρ_{01}				-0.665
NConcept				60
NParticipant				32
ICCConcept				0.084
ICCParticipant				0.408
Observations				25345
R^2				0.375
AIC				-20712.489
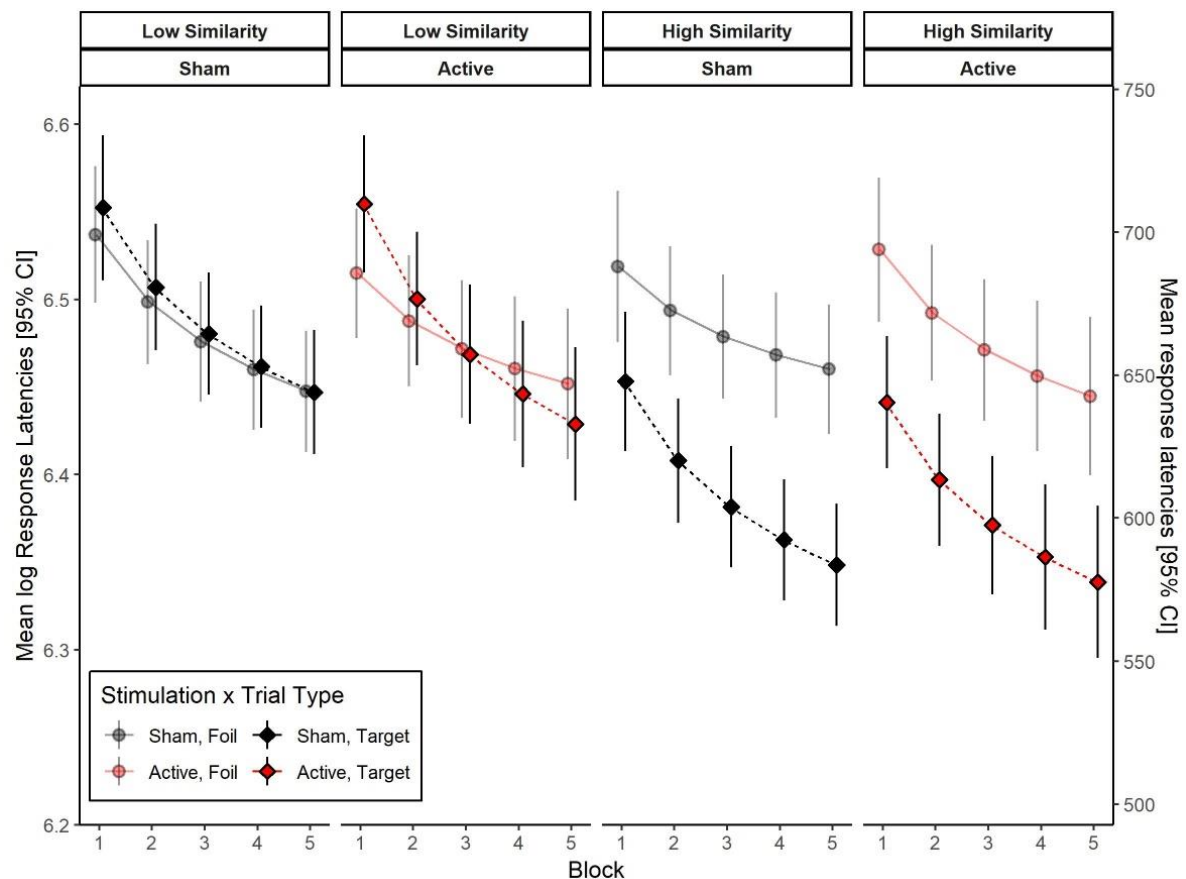
Figure 7.4. Log-transformed response latencies [95% CI] and exponentiated response times (right axis), as a function of Block and Trial type, panelled by Phonological Similarity and Stimulation Type. Foils reflect correct rejections.

7.4.1.5 Moderating Effects of Phonological Memory.

In some studies, the effects of tDCS have been shown to vary as a function of individual baseline performance (e.g., Benwell et al., 2015; Berryhill & Jones, 2012; c.f. Learmonth et al., 2017). This study's secondary aim was to assess whether there were moderating effects of phonological memory performance in the response to tDCS. Better phonological working memory abilities are thought to be associated with better word learning abilities and therefore could interact with stimulation effects. The scaled scores on the phonological composite measure were bimodally distributed in this sample, so a median split was applied to these data to separate participants into groups of lower (<= 95) and higher (>

95) phonological memory scores. The factor was centre sum-coded for inclusion as a fixed effect in the analysis.

Phonological memory group was entered as an additional fixed effect with all other predictors to examine whether this variable moderated the interaction effect observed in the response latency data (see Table 7.5). Phonological working memory performance did appear to produce a weak moderating effect on the earlier observed four-way interaction. This five-way interaction showed that the previously observed effect of active stimulation was only present for the group of participants with *higher* phonological memory (see Figure 7.5). A parallel analysis conducted on the discrimination data (Table 7.6 for coefficients) revealed that greater phonological working memory abilities were associated with enhanced learning performance over blocks – hits increased and false alarms decreased more steeply over exposure compared to participants with lower phonological working memory. This effect was particularly pronounced for the lower phonological similarity items, whilst there was less of a difference between subgroups in their responses to higher phonological similarity items. Phonological memory ability did not interact with stimulation in any way (Figure 7.6).

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Table 7.5.

LMM Estimates for Log Response Latencies Including Phonological Memory as a

Moderator

	B	*95% CI*	*t*	*p*
(Intercept)	6.539	6.50 – 6.57	355.86	**<.001**
Phonological Memory Group (Lower, Higher) [PMem]	-0.015	-0.08 – 0.05	-0.43	.668
Stimulation (Sham, Active)	-0.009	-0.04 – 0.02	-0.67	.507
log(Block)	-0.059	-0.07 – -0.05	-9.10	**<.001**
Phonological Similarity (Low, High) [PSim]	-0.05	-0.07 – -0.03	-6.34	**<.001**
Trial Type (Foil, Target)	0.026	0.01 – 0.04	4.03	**<.001**
PMem:Stimulation	-0.002	-0.05 – 0.05	-0.09	.931
PMem:log(Block)	0.014	-0.01 – 0.04	1.08	.289
PMem:PSim	-0.01	-0.04 – 0.02	-0.66	.512
PMem:Trial Type	-0.04	-0.06 – -0.02	-3.21	**.001**
Stimulation:log(Block)	0.002	-0.02 – 0.02	0.20	.846
Stimulation:PSim	0.01	-0.01 – 0.03	0.98	.328
Stimulation:Trial Type	0.026	0.00 – 0.05	2.06	**.039**
log(Block):PSim	0.004	-0.01 – 0.01	0.88	.382
log(Block):Trial Type	-0.026	-0.04 – -0.01	-4.68	**<.001**
PSim:Trial Type	-0.103	-0.12 – -0.08	-9.66	**<.001**
PMem:Stimulation:log(Block)	0.017	-0.02 – 0.05	0.95	.346
PMem:Stimulation:PSim	-0.01	-0.05 – 0.03	-0.50	.620
PMem:log(Block):PSim	0.002	-0.02 – 0.02	0.26	.792
PMem:Stimulation:Trial Type	0.046	-0.00 – 0.09	1.85	.064
PMem:log(Block):Trial Type	0.007	-0.01 – 0.03	0.62	.538
PMem:PSim:Trial Type	-0.004	-0.04 – 0.04	-0.20	.839
Stimulation:log(Block):PSim	-0.01	-0.03 – 0.01	-1.08	.279
Stimulation:log(Block):Trial Type	-0.031	-0.05 – -0.01	-2.89	**.004**
Stimulation:PSim:Trial Type	-0.051	-0.09 – -0.01	-2.45	**.014**
log(Block):PSim:Trial Type	0.007	-0.01 – 0.02	0.76	.448
PMem:Stimulation:log(Block):PSim	0.002	-0.03 – 0.04	0.09	.930
PMem:Stimulation:log(Block):Trial Type	-0.04	-0.08 – 0.00	-1.89	.059
PMem:Stimulation:PSim:Trial Type	-0.094	-0.18 – -0.01	-2.30	**.021**
PMem:log(Block):PSim:Trial Type	0.004	-0.03 – 0.04	0.24	.813
Stimulation:log(Block):PSim:Trial Type	0.048	0.01 – 0.08	2.73	**.006**
PMem:Stimulation:log(Block):PSim:Trial Type	0.072	0.00 – 0.14	2.03	**.042**

Table 7.5 Continued

Random Parts	
σ^2	0.025
τ_{00}, Concept	0.004
τ_{00}, Participants	0.024
ρ_{01}	-0.674
NConcept	60
NParticipants	32
ICCConcept	0.079
ICCParticipants	0.454
Observations	25345
R^2	.383
AIC	-20922.12
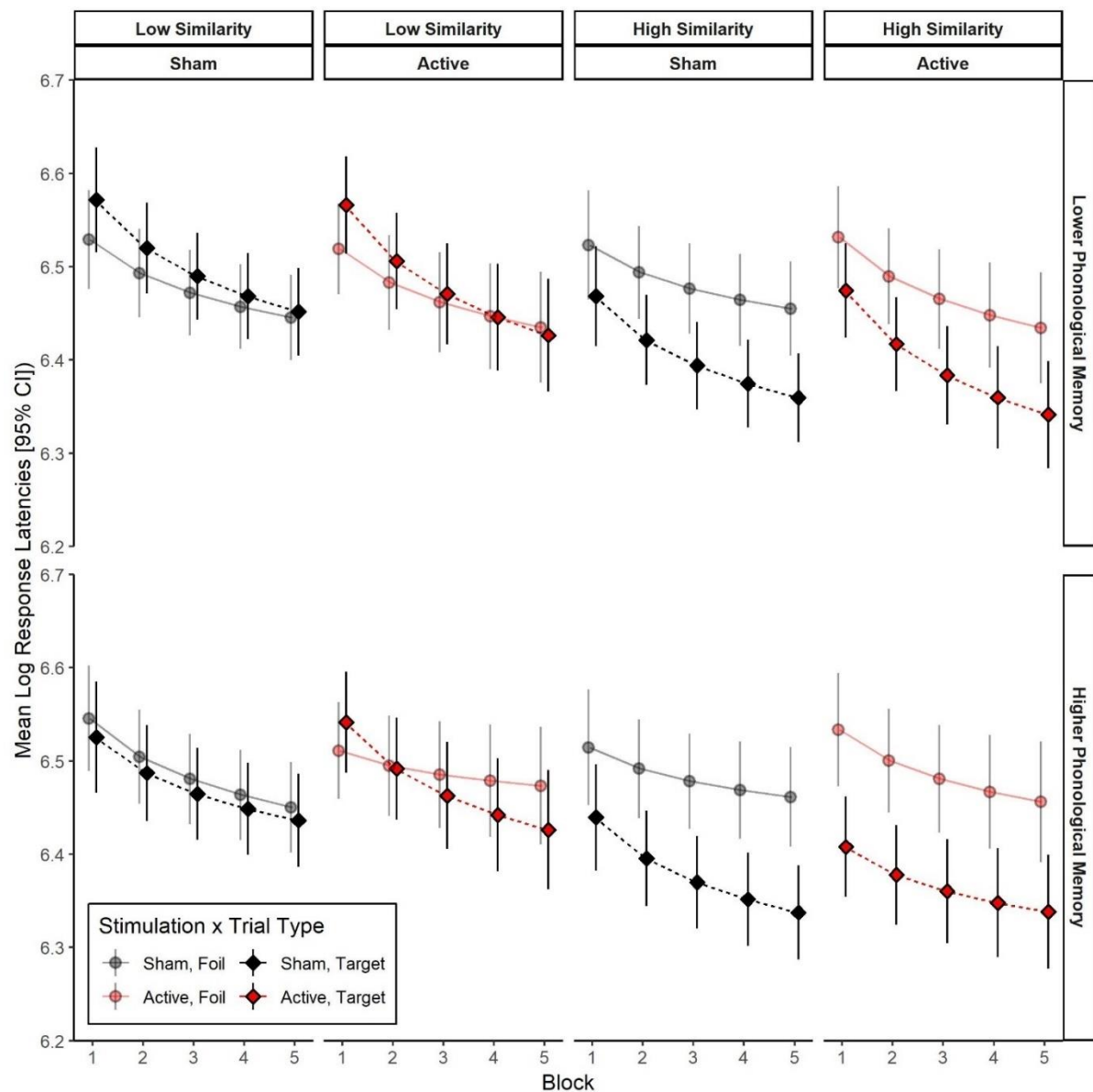
Figure 7.5. Mean log response latencies [95% CI] in each Block, separated by Trial Type,

Phonological Similarity and Stimulation Type, show separately for participants with Lower

(top) and Higher (bottom) Phonological Memory scores. Foils reflect correct rejections.

Table 7.6.

Model Coefficients from GLMM including Phonological Memory Group as a Moderator.

	lnOR	95% CI	z	p
(Intercept)	-0.408	-0.70 – -0.12	-2.77	**.006**
Phonological Memory Group (Lower, Higher) [PMem]	0.095	-0.28 – 0.47	0.50	.618
Stimulation (Sham, Active)	0.056	-0.19 – 0.31	0.44	.661
log(Block)	0.26	0.14 – 0.38	4.35	**<.001**
Combined Phonological Similarity (Low, High) [PSim]	1.749	1.61 – 1.88	25.46	**<.001**
Trial Type (Foil, Target)	0.86	0.75 – 0.97	15.88	**<.001**
PMem:Stimulation	0.127	-0.35 – 0.60	0.52	.601
PMem:log(Block)	0.043	-0.17 – 0.25	0.40	.690
Stimulation:log(Block)	0.021	-0.16 – 0.20	0.23	.816
PMem:PSim	-0.093	-0.31 – 0.12	-0.85	.393
Stimulation:PSim	-0.193	-0.43 – 0.04	-1.62	.104
log(Block):PSim	-0.091	-0.21 – 0.02	-1.55	.122
PMem:Trial Type	-0.081	-0.28 – 0.12	-0.78	.433
Stimulation:Trial Type	-0.102	-0.31 – 0.10	-0.97	.330
log(Block):Trial Type	0.933	0.84 – 1.03	18.82	**<.001**
PSim:Trial Type	-0.008	-0.23 – 0.21	-0.07	.946
PMem:Stimulation:log(Block)	-0.043	-0.40 – 0.31	-0.24	.811
PMem:Stimulation:PSim	-0.304	-0.73 – 0.13	-1.39	.165
PMem:log(Block):PSim	0.122	-0.07 – 0.31	1.24	.214
Stimulation:log(Block):PSim	0.061	-0.13 – 0.26	0.62	.537
PMem:Stimulation:Trial Type	-0.238	-0.64 – 0.17	-1.15	.249
PMem:log(Block):Trial Type	-0.281	-0.47 – -0.10	-2.99	**.003**
Stimulation:log(Block):Trial Type	-0.028	-0.21 – 0.16	-0.29	.769
PMem:PSim:Trial Type	-0.411	-0.83 – 0.01	-1.93	.054
Stimulation:PSim:Trial Type	-0.043	-0.47 – 0.38	-0.20	.845
log(Block):PSim:Trial Type	-0.085	-0.29 – 0.12	-0.83	.405
PMem:Stimulation:log(Block):PSim	0.206	-0.18 – 0.60	1.04	.301
PMem:Stimulation:log(Block):Trial Type	0.081	-0.29 – 0.45	0.43	.668
PMem:Stimulation:PSim:Trial Type	0.006	-0.83 – 0.84	0.02	.988
PMem:log(Block):PSim:Trial Type	0.394	0.01 – 0.77	2.04	**.042**
Stimulation:log(Block):PSim:Trial Type	-0.111	-0.49 – 0.27	-0.57	.571
PMem:Stimulation:log(Block):PSim:Trial Type	-0.183	-0.94 – 0.57	-0.47	.636

Table 7.6 continued.

Random Parts	
σ^2	
τ_{00}, Concept	1.36
τ_{00}, Participant	1.066
ρ_{01}	-0.687
NConcept	60
NParticipant	32
ICCConcept	0.238
ICCParticipant	0.186
Observations	37190
Tjur's D/R2	0.375
AIC	36436.86
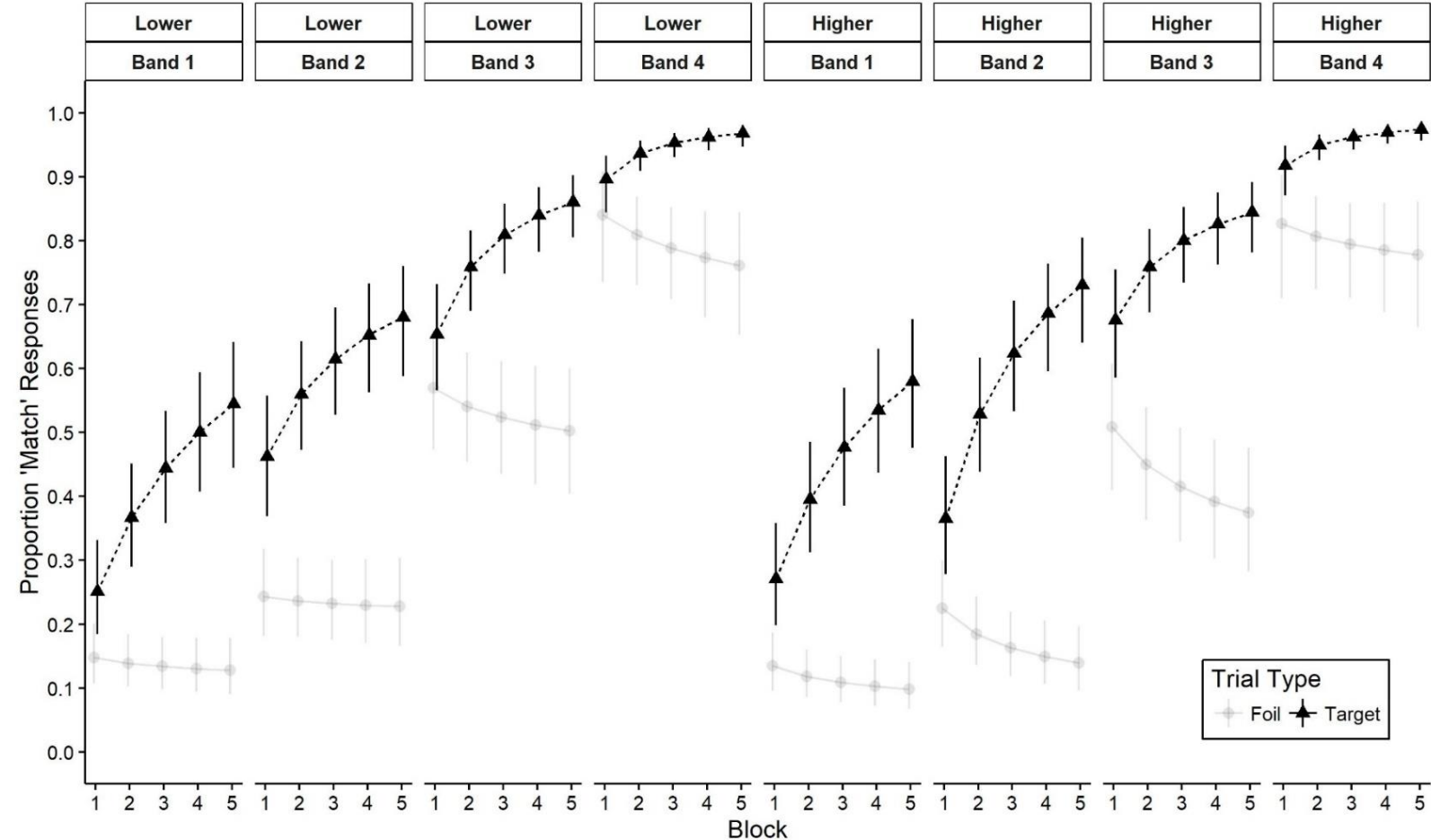
Figure 7.6. Proportion 'Match' responses [95% CI] over blocks, for each Trial Type, separated by Phonological Similarity and Phonological

Working Memory Abilities.

7.5 Translation

Three participants were lost to follow-up so model estimates at this timepoint are only based on 29 participants. Seven trials were lost during offline recoding due to technical problems with E-Prime, leaving a total of 11,144 data points in the final dataset. The final parsimonious model included a by-participant random intercept with random slopes of Stimulation and Raw PNLD, plus an intercept for Concepts with slopes for Session and Stimulation. Random effects correlations were successfully refit and improved model fit $(AIC_{DIFF} = 77.13)$.

$$glmer(Accuracy \sim Stimulation*Session*Phonological\ Similarity +$$
$$(1 + Stimulation + RawPNLD\ |\ Participant) +$$
$$(1 + Stimulation + Session\ |\ Concept),$$
$$family = binomial(\text{``logit''}), \dots$$

Figure 7.7 shows the Translation accuracy data and model estimates are presented in Table 7.7. Translation accuracy was stable from Immediate to Day After sessions but decreased slightly overall at Follow-up a week later. Translation accuracy improved with increasing phonetic similarity but only the correct responses to targets in the highest phonological similarity band were significantly greater compared to the band below, probably due to the substantial variability in task performance. This pattern was relatively stable across sessions but showed some fluctuation for targets in the highest phonological similarity band: translation accuracy for these items decreased slightly from Immediate to Day After sessions, but then improved slightly at Follow-up. Stimulation type did not moderate any of these effects.
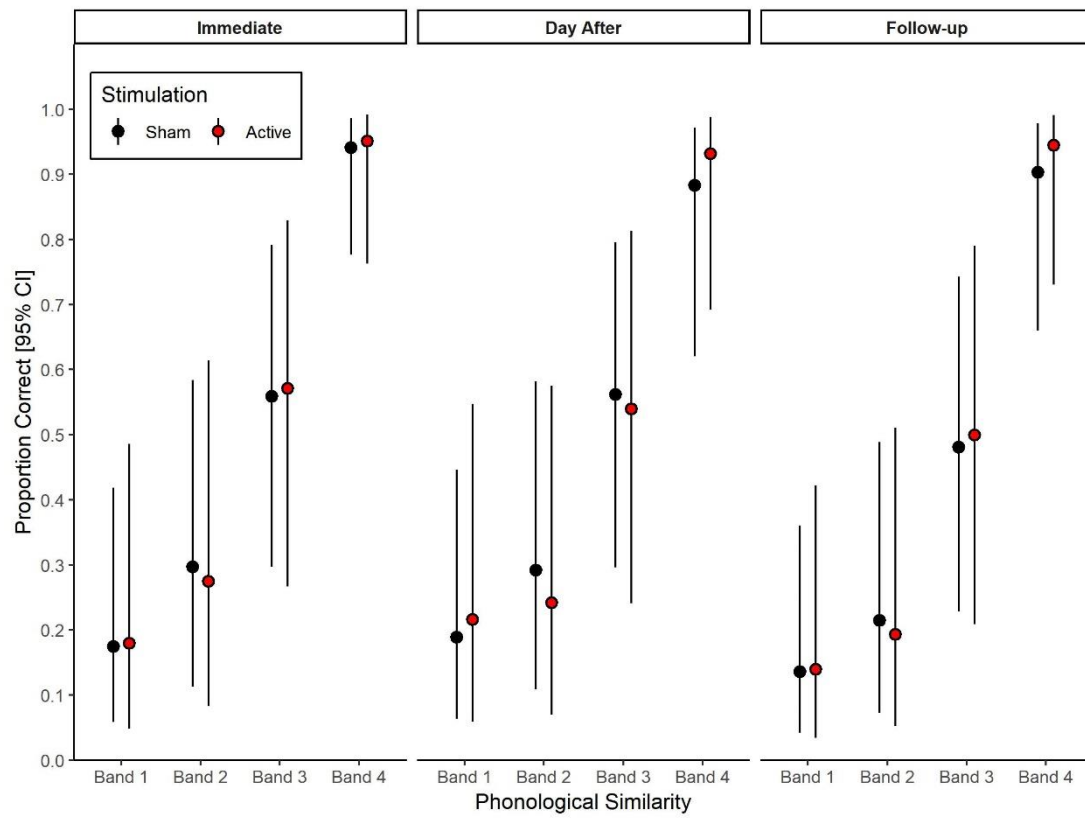
Figure 7.7. Proportion correct [95% CI] translation trials separated by Session, Stimulation

Type and Phonological Similarity.

Table 7.7.

GLMM Estimates for Translation Accuracy

	Translation Accuracy			
	InOR	*95% CI*	*z*	*p*
(Intercept)	-0.159	-1.01 – 0.69	-0.368	.713
Stimulation (Sham, Active)	0.057	-0.24 – 0.36	0.373	.709
Session: Immediate vs. Day After (Session1)	-0.098	-0.24 – 0.04	-1.378	.168
Session: Day After vs. Follow-up (Session2)	-0.244	-0.39 – -0.10	-3.282	.001
Phonological Similarity: Band 1 vs. Band 2 (PSim1)	0.483	-1.19 – 2.15	0.567	.571
Phonological Similarity: Band 2 vs. Band 3 (PSim2)	1.237	-0.29 – 2.76	1.591	.112
Phonological Similarity: Band 3 vs. Band 4 (PSim3)	2.427	0.67 – 4.18	2.711	.007
Stimulation:Session1	0.012	-0.23 – 0.26	0.096	.924
Stimulation:Session2	0.056	-0.20 – 0.31	0.431	.666
Stimulation:PSim1	-0.246	-0.92 – 0.42	-0.72	.472
Stimulation:PSim2	0.178	-0.44 – 0.80	0.563	.573
Stimulation:PSim3	0.453	-0.32 – 1.23	1.146	.252
Session1:PSim1	-0.265	-0.64 – 0.11	-1.382	.167
Session2:PSim1	0.117	-0.28 – 0.51	0.582	.561
Session1:PSim2	0.043	-0.30 – 0.39	0.246	.805
Session2:PSim2	0.104	-0.26 – 0.46	0.564	.573
Session1:PSim3	-0.491	-0.94 – -0.05	-2.166	.030
Session2:PSim3	0.463	0.01 – 0.91	2.012	.044
Stimulation:Session1:PSim1	-0.283	-0.96 – 0.39	-0.822	.411
Stimulation:Session2:PSim1	0.262	-0.45 – 0.98	0.719	.472
Stimulation:Session1:PSim2	0.009	-0.60 – 0.62	0.027	.978
Stimulation:Session2:PSim2	0.043	-0.60 – 0.69	0.131	.895
Stimulation:Session1:PSim3	0.537	-0.25 – 1.33	1.33	.184
Stimulation:Session2:PSim3	-0.15	-0.95 – 0.65	-0.366	.714

Random Parts	
$\tau_{00, Concepts}$	0.051
$\tau_{00, Participants}$	0.679
$N_{Concepts}$	60
$N_{Participants}$	32
$ICC_{Concepts}$	0.005
$ICC_{Participants}$	0.069
Observations	11144
Tjur's D	0.469
AIC	9713.058

7.5.1 Response Types

Errors were coded using the same criteria as in Chapter 5. Don't know and phonological errors accounted for the most errors, followed by unrelated, with low rates of semantic, mixed and visual errors. As is clear from Figure 7.8, the distribution of errors in sham and active stimulation sessions is practically identical, suggesting no obvious influence of tDCS on the errors made during translation.
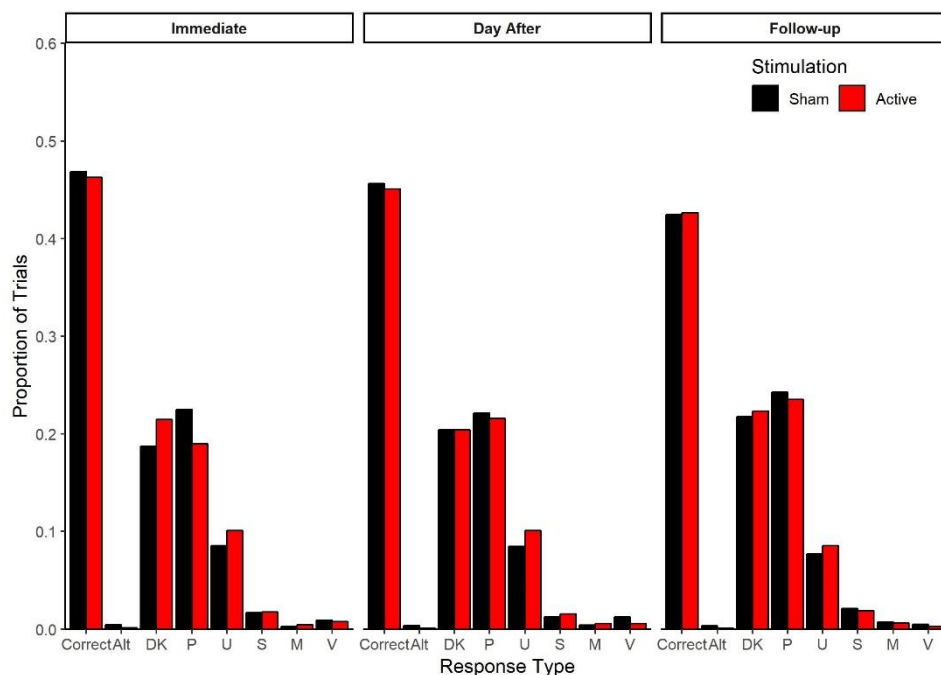
Figure 7.8. Proportion of trials for each response type, separated by session and stimulation type.

7.5.2 Moderating Effects of Phonological Working Memory

 With a view to addressing the secondary aims of this study, phonological memory group was included as a fixed factor in the translation GLMM. This analysis revealed a weak moderating effect of phonological memory group that showed differential effects of tDCS on translation performance that affected translation success for targets in the two higher bands of phonological similarity, between immediate and short-term testing points (see Table 7.8 for coefficients). Figure 7.8 shows that in the highest bands of phonological similarity,

performance was similar for targets learned during active and sham stimulation, immediately following the associative learning task for both subgroups. However, the day after stimulation, performance dropped for targets learned during active and sham to a similar degree for the higher phonological memory participants. For participants with lower phonological memory, active stimulation appeared to promote a maintenance effect for these same items, relative to sham. This pattern of response was stable at follow-up. Additionally, figure 7.9 also shows a pattern of results that may suggest potential opposing effects of tDCS for the two subgroups for more moderately similar targets. Translation was marginally better for targets learned under active compared to sham conditions in the lower phonological memory participants, whereas the opposite was true for the higher phonological memory participants. However, the fluctuation in the pattern of these results across sessions, in the context of the considerable variability in task performance suggest that these effects could possibly be an artefact of low power and a lack of precision for this task/analysis.
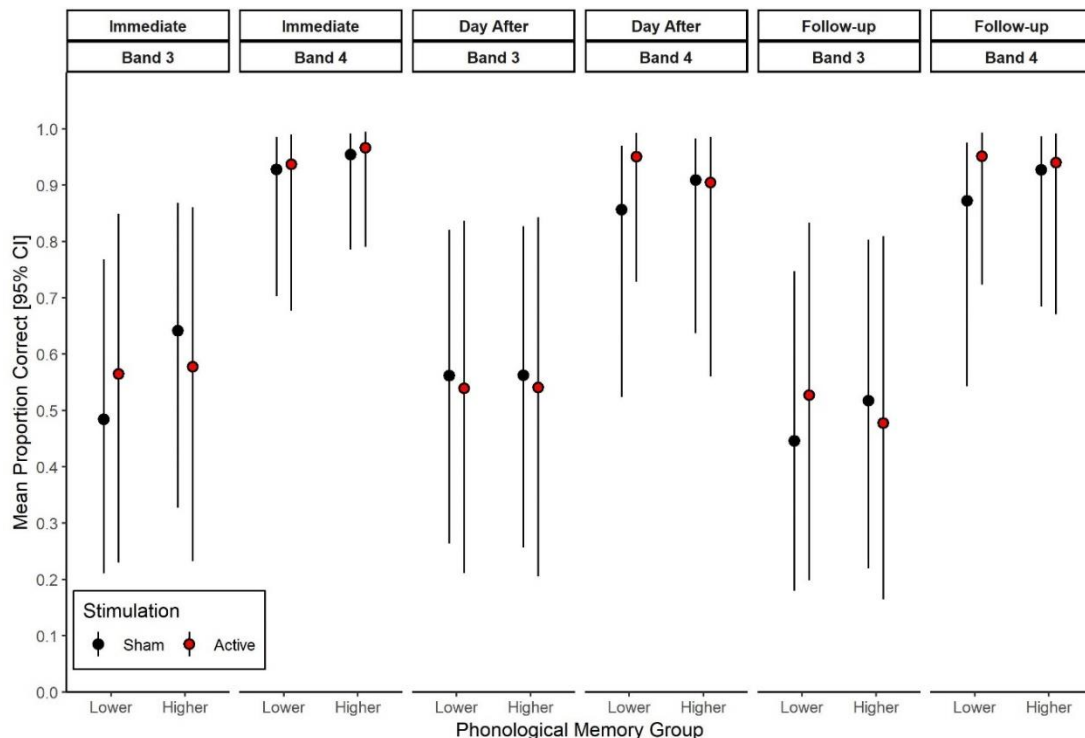
Figure 7.9. Proportion correct [95% CI] translation trials in the two highest phonological similarity bands, separated by Session, Stimulation and Phonological Memory subgroup.

Table 7.8.

GLMM Model Coefficients for Translation Accuracy including Phonological Working Memory Group.

	Translation Accuracy			
	lnOR	*95% CI*	*z*	*p*
(Intercept)	-0.16	-1.01 – 0.70	-0.36	.720
Phonological Memory Group (Lower, Higher) [PMem]	0.04	-1.20 – 1.27	0.06	.956
Stimulation (Sham, Active)	0.06	-0.24 – 0.36	0.40	.687
Session: Immediate vs. Day After [Session1]	-0.11	-0.24 – 0.03	-1.52	.129
Session: Day After vs. Follow-up [Session2]	-0.24	-0.38 – -0.10	-3.28	**.001**
Phonological Similarity: Band 1 vs. Band 2 (PSim1)	0.48	-1.20 – 2.16	0.56	.576
Phonological Similarity: Band 2 vs. Band 3 (PSim2)	1.25	-0.29 – 2.78	1.60	.111
Phonological Similarity: Band 3 vs. Band 4 (PSim3)	2.44	0.68 – 4.21	2.71	**.007**
PMem:Stimulation	-0.23	-0.66 – 0.19	-1.08	.282
PMem:Session1	-0.40	-0.65 – -0.16	-3.20	**.001**
PMem:Session2	0.16	-0.10 – 0.42	1.19	.233
Stimulation:Session1	0.01	-0.24 – 0.25	0.04	.965
Stimulation:Session2	0.08	-0.18 – 0.33	0.57	.568
PMem:PSim1	-0.21	-0.60 – 0.19	-1.03	.303
PMem:PSim2	0.34	-0.03 – 0.70	1.81	.070
PMem:PSim3	0.09	-0.33 – 0.51	0.41	.681
Stimulation:PSim1	-0.25	-0.93 – 0.42	-0.73	.465
Stimulation:PSim2	0.18	-0.45 – 0.80	0.55	.580
Stimulation:PSim3	0.47	-0.31 – 1.25	1.18	.238
Session1:PSim1	-0.28	-0.65 – 0.10	-1.45	.147
Session2:PSim1	0.14	-0.26 – 0.53	0.68	.498
Session1:PSim2	0.05	-0.30 – 0.39	0.27	.785
Session2:PSim2	0.10	-0.27 – 0.46	0.52	.605
Session1:PSim3	-0.51	-0.96 – -0.06	-2.25	**.025**
Session2:PSim3	0.46	0.01 – 0.91	1.99	**.047**
PMem:Stimulation:Session1	-0.08	-0.58 – 0.41	-0.33	.740
PMem:Stimulation:Session2	-0.33	-0.85 – 0.19	-1.24	.214
PMem:Stimulation:PSim1	0.36	-0.28 – 0.99	1.10	.272
PMem:Stimulation:PSim2	-0.52	-1.08 – 0.04	-1.80	.071
PMem:Stimulation:PSim3	-0.27	-0.98 – 0.43	-0.76	.449
PMem:Session1:PSim1	-0.53	-1.20 – 0.15	-1.53	.126
PMem:Session2:PSim1	0.48	-0.24 – 1.19	1.30	.194
PMem:Session1:PSim2	0.27	-0.35 – 0.88	0.85	.398
PMem:Session2:PSim2	-0.39	-1.03 – 0.26	-1.17	.243
PMem:Session1:PSim3	-0.32	-1.12 – 0.48	-0.79	.430
PMem:Session2:PSim3	0.27	-0.54 – 1.07	0.65	.518

Table 7.8 continued

Stimulation:Session1:PSim1	-0.28	-0.96 – 0.39	-0.82	.411
Stimulation:Session2:PSim1	0.24	-0.47 – 0.96	0.67	.506
Stimulation:Session1:PSim2	0.03	-0.58 – 0.64	0.10	.920
Stimulation:Session2:PSim2	0.06	-0.59 – 0.71	0.18	.856
Stimulation:Session1:PSim3	0.48	-0.31 – 1.28	1.19	.234
Stimulation:Session2:PSim3	-0.11	-0.92 – 0.69	-0.28	.782
PMem:Stimulation:Session1:PSim1	0.56	-0.81 – 1.91	0.80	.424
PMem:Stimulation:Session2:PSim1	0.36	-1.08 – 1.81	0.49	.625
PMem:Stimulation:Session1:PSim2	0.45	-0.79 – 1.68	0.71	.476
PMem:Stimulation:Session2:PSim2	-0.20	-1.50 – 1.11	-0.30	.768
PMem:Stimulation:Session1:PSim3	-1.98	-3.58 – -0.38	-2.42	**.015**
PMem:Stimulation:Session2:PSim3	0.86	-0.77 – 2.48	1.04	.301

Random Parts

$T_{00, Concepts}$	0.05
$T_{00, Participants}$	0.689
$N_{Concepts}$	60
$N_{Participants}$	32
$ICC_{Concepts}$	0.005
$ICC_{Participants}$	0.07
Observations	11144
Deviance	8804.321

7.5.1.1 Response Type

Including phonological working memory group had little impact on the relative frequency of different types of errors.

7.6 Summary.

Taken together these data suggest that participants were able to learn novel target Dutch words to a reasonable extent, relying heavily on phonological similarity of novel words to known words to make judgements about translation equivalence between languages. Better phonological memory performance enhanced participants' discrimination

performance, particularly for targets with lower phonological similarity. TDCS produced a

subtle impact on learning and translation behaviour but the nature of these effects differed as

a function of task and phonological memory subgroup. During learning, tDCS did not

moderate discrimination performance at the whole or subgroup level. However, reduction in

response times to less phonologically similar foils were shallower relative targets in active

compared to sham conditions, but only for participants who had higher phonological memory

abilities. In translation, tDCS-induced facilitation was observed in participants with lower

phonological memory abilities to targets that were best learned/most easily identified from

the outset. There was little evidence for a moderating effect of tDCS on the types of errors.

The reported effects are subtle but may be indicative of complex moderator effects at the task

and participant level on tDCS response.

7.7 Discussion

The aim of the present study was to extend the scope of previous work showing

facilitation of learning and consolidation of novel pseudowords under active tDCS applied to

left temporoparietal regions (Fiori et al., 2011; Flöel et al., 2008; Meinzer et al., 2014;

Perceval et al., 2017; Savill et al., 2015). The present study tested whether previous findings

could be extended to real foreign language vocabulary. In the first study to do so, the

expected effects of tDCS were examined in the context of two key determinants of word

learning success at the stimulus and participant level: phonological similarity of novel words

to known words (Ecke & Hall, 2014; Ringbom, 2007; Vitevitch & Luce, 2016), and

participants' phonological working memory ability (Gathercole, 2006; Gathercole &

Baddeley, 2014; Gupta & Tisdale, 2009a). The key findings are discussed in each section

below.

7.7.1 Learning Effects

In the present study, the overall pattern of performance was consistent with that observed in chapter five. Phonological similarity acted as a pertinent cue to meaning, resulting in a strong initial bias to say 'match' to highly similar foils and targets. This was coupled with overall faster response times for more phonologically similar targets relative to foils. As in chapter five, learning occurred over and above the phonological similarity bias: hit rates increased considerably for targets in all phonological similarity bands, whilst false alarm rates remained stable, or decreased, over the five learning blocks, with concurrent improvements in decision times. As per the previous study, targets more phonologically similar to English were translated with greater success than less phonologically similar targets, a finding consistent with the cognate form similarity assumption (Hall, 2002). Again, performance on the backward translation task was relatively stable over the earlier two time points, with a decay in performance over the week follow-up period, although there was considerable between-participant variability. In addition, participants with better phonological working memory abilities showed a general advantage in discriminating between target and foil stimuli in accuracy and response time measures during learning and a weak general advantage in translation success. These patterns of results are consistent with large body of work that phonological working memory abilities underpin novel word learning (Gathercole, 2006; Gupta & Tisdale, 2009a).

7.7.2 tDCS Effects

The effects of tDCS on learning and translation performance in this study were subtle and varied as a function of combined task and participant-level factors. At the overall group level, tDCS appeared to specifically moderate the improvement in decision times over blocks during the learning task but there was little observable tDCS effect at the group level on translation performance. Investigating the influence of participants' phonological working

memory abilities revealed that the effects of tDCS on response times were differentially moderated by this factor, as a function of task demands. During learning, tDCS moderated the rate of improvement in response times to correctly reject foils with less phonological overlap with English object names, but only for participants with higher phonological memory abilities. Conversely, participants with lower phonological working memory abilities showed improved performance during translation for targets with the greatest phonological similarity to English.

The observed effects of tDCS might suggest that a certain level of learning, or robustness in novel representations, may be needed for tDCS to have an observable effect on behavioural performance. The effect of tDCS on learning performance is specific to more difficult items amongst participants with greater learning capacity. In terms of accuracy, participants with higher phonological working memory show greater efficiency in learning; more rapidly increasing hit rates, with simultaneous decrease in false alarms. This pattern of responses suggests a more robust representation or maintenance of the word forms for foils, in these participants relative to participants with lower phonological working memory abilities. Given the relative infrequency of foils and potentially increased maintenance of representations for foil word forms, the noise induced by tDCS may act on residual noise, increasing interference during the correct rejection process for these items. This may underpin the relative decrease in slope magnitude for decision times under active relative to sham stimulation for this subgroup.

In contrast, the effects of tDCS on translation performance were observed for the targets with greatest phonological overlap with English, in the subgroup of participants with poorer working memory abilities. Maintenance of translation success at intermediate and longer term testing points, for the most similar targets was enhanced for participants with lower phonological working memory for stimuli learned under active relative to sham

stimulation. For participants with lower phonological working memory, processing of novel phonological forms may be more difficult, resulting in a stronger bias towards phonologically similar targets. Although both subgroups showed comparable learning slopes for band 3 and band 4 targets in Figure 7.7, participants with lower phonological memory abilities showed less of a reduction in false alarm rates over blocks for phonologically similar foils. If for these participants, differences in phonological form are not readily apparent, then representations of the phonological codes for targets like /boek/, and competing foils like /boeg/, will be linked to existing representation of /book/ more readily than for participants with greater phonological working memory abilities. Stochastic resonance induced by tDCS may increase the activation of the noise associated with the foils to a greater degree that further strengthens this generalised link between form and meaning for these participants. For participants with weaker phonological working memory abilities, it is possible that tDCS increased the activation of the network during learning and facilitated the binding between these broader phonological representations and semantic information in long term memory. Offline, this manifests as an advantage in backward translation relative to sham. Taken together, the above findings may provide tentative support for the network-state dependency account (Miniussi et al., 2013). Despite the relatively weak effects, the present findings highlight the need to examine task-critical individual differences to better understand tDCS effects, in line with some recent studies (Benwell et al., 2015; M E Berryhill & Jones, 2012; Krause & Cohen Kadosh, 2014; G. Perceval et al., 2017)

7.7.3 Limitations & Future Direction

In the present study we employed a single session stimulation paradigm, comparing the effects of active and sham tDCS within participants, over consecutive days (cf. Savill et al., 2015). In doing so, we aimed to lay a foundation for future studies of real foreign language learning using this technique. However, the observed effects were weaker than

reported in previous single session studies. There are a number of potential explanations that could explain such an effect. First, the stimuli in this study were real foreign language words from a closely related but completely unfamiliar language for our participants. Subtleties in the differences between the phonological inventories, as well as additional novel phonemes may have increased the perceptual difficulty of the task, relative to the use of native-language derived pseudowords. Second, in an attempt to combat a phonological similarity bias, we included foils that were phonologically similar to the target words in Dutch, which may have increased the number of possible exemplars encountered during the task compared to the task originally employed by Floel et al. (2008) in their tDCS study. This increase in task difficulty may have limited learning performance for participants or resulted in less robust representations overall. Examination of stimulus features may be a necessary step in understanding the interaction between tDCS and the state of the network during word learning.

As well as the characteristics of individual stimuli the relative make-up of word lists may be an important factor to consider when examining real foreign language learning and subsequent recall. For example, Jefferies, Frankish and Lambon Ralph (2006) showed in a group of native-English speakers, that as the ratio of nonwords to words increased, accuracy of production at the phoneme level decreased for words. Increasing the number of less phonologically similar targets may be helpful in reducing some of the ceiling effects to more phonologically similar targets, in combination with foils. This may be enough to modulate the saliency of less similar novel words and alter the learning outcome, and thus the relative state of the learning network. Additionally, direct comparisons of effects of neurostimulation applied to left temporoparietal regions during acquisition of pseudowords and/or novel foreign language words, using the same paradigm, may highlight differences and similarities

in response to tDCS that may help to refine discussion of the role of temporoparietal region in word learning, more generally (cf. Lindsay and Gaskell, 2010).

Finally, the nature and timing of the task used to probe lexical integration and consolidation of novel forms needs consideration in future studies. The translation task was difficult for most participants and performance was highly variable, with a relative floor for items with the least phonological overlap. This finding reflects the need for a subtler task to probe consolidation in these very early stages of learning. Previous studies utilising similar associative learning paradigms have employed semantic decision (Dobel, Junghöfer, et al., 2009; Dobel, Lagemann, et al., 2009) or phonological interference tasks to probe lexical integration (Gaskell & Dumay, 2003). In addition, asking participants to perform the backward translation task immediately after learning without feedback may have interfered with ongoing consolidation of weaker form-meaning links, impairing consolidation further and interrupting ongoing processing in over-active regions immediately following tDCS. Au et al. (2017) proposed that enhanced consolidation effects following a single stimulation session may evolve over time. Multiple stimulation sessions may enhance the effect of tDCS on learning (e.g., Meinzer et al., 2014). Longitudinal designs designed to probe consolidation over short (i.e., 30 minutes, 3 hours) and longer durations (e.g., 24 hours, 1-week, 1-month) following single sessions should be considered in order to better understand the effects of tDCS on complex cognitive processing (cf. Savill et al., 2015). Insight from such studies would provide impetus for the development of optimal dosing protocols that may enhance effects of tDCS further.

7.7.4 Conclusion

The present study revealed robust effects of phonological similarity on word learning and translation performance. The effects of tDCS were subtle and resulted in differential effects as a function of task and participant characteristics. The pattern of results provided

tentative support for the network-state dependency account of tDCS and highlight the need to examine stimulus, task and participant-level variables as moderators of stimulation effects. .

Chapter 8: General Discussion

8.0 Summary of Main Findings

The aim of this thesis was to examine network-state dependent effects of tDCS in the context of naming and word learning studies. The first empirical study failed to replicate previously reported facilitative effects of active tDCS on naming response times. Repetition priming effects were largely identical for active and sham sessions, irrespective of whether stimulation was applied to left IFG or STG sites. For studies two and three, a more sensitive paradigm was developed to emulate some of the processes implicated in the very early stages of foreign language learning. Study two demonstrated that this paradigm was sensitive to several factors that reflect relative differences in network states in response to the task. First, strong effects of phonological similarity reflect relative differences in co-activation of known English words from unknown foreign language words. Second, learning success was predicted by participants' baseline phonological working memory abilities. Third, the paradigm showed sensitivity to the effects of bilingual experience. By demonstrating that the paradigm could successfully illicit both strong and subtler effects on learning performance, the possibility of detecting modulation of behaviour with tDCS was improved.

Study three tested the effects of tDCS on learning of real foreign language stimuli and examined the effects of task and participant-level factors as moderators of potential effects. There were subtle effects of tDCS on word learning that were driven for by complex interactions between stimulus, task and participant-level characteristics. These data tentatively suggest that an optimal level of learning, or activation of newly learned representations, may be needed in order to observe tDCS effects, consistent with stochastic resonance and network-state dependency accounts of tDCS (Fertonani & Miniussi, 2017; Miniussi et al., 2013).

8.1 Main Contributions

The studies in this thesis directly tested the network-state dependency account of tDCS affects, through manipulation of key methodological factors that may be crucial for facilitation of language performance in healthy adults. The approach taken to stimulus control and examination of moderating factors is something that has rarely been explicitly considered in tDCS studies of naming and word learning. Consideration of these factors is desperately needed to understand how specific features of an experimental task interact with stimulation. The studies in this thesis capitalised on robust behavioural effects in naming and learning, in order to identify even subtle influences of tDCS. In study one we capitalised on repetition priming phenomena to examine the effects of lexical pre-activation on subsequent naming performance and the effects of tDCS. In study two, we conducted a full investigation of the behavioural effects of the novel word learning paradigm for more effective reference of tDCS effects observed in study three. As well as a model for the tDCS study, study two highlighted the robustness of the bilingual word learning advantage in an associative word learning task but left us with questions regarding the locus of this effect. Additionally, we note that most language processing studies utilising tDCS have not considered the linguistic experience of their participants, potentially confounding their findings. On the basis that bilingual experience affects naming performance in general (Kroll et al., 2012; Runnqvist et al., 2012), as a well as word learning (Hirosh & Degani, 2018) and more fundamental perceptual abilities (T. C. Zhao & Kuhl, 2018), future language studies employing tDCS should control or examine linguistic experience, as the response of an already 'altered' network is likely to differ substantially to tDCS in monolinguals.

One of the key contributions of this thesis is an emphasis on trying to understand how specific participant, task, and stimulus-level characteristics interact with tDCS. There are few studies that include a no-stimulation arm or reference to any behavioural pilot of a study in a

population of interest, which may be useful in understanding how the simple engagement in the tDCS protocol impacts performance in general. Careful examination of these factors may enhance the ability of researchers to design more effective and reliable protocols for the study of cognition and enhancement of treatment effects. A careful, step-wise approach to study design, with an emphasis on refinement, replication and collaboration (for an excellent recent example, (Cattaneo et al., 2016; Vannorsdall et al., 2016, 2018) rather than novelty, would likely enhance the credibility and reliability of the field.

A second contribution to the field is the consistent approach to statistical analysis within this thesis. Most previous studies utilise ANOVA-type analyses that rely on aggregation of data within participants and/or items. All studies presented in this thesis utilised mixed effects models. Mixed effects models offer several advantages over ANOVA (R. H. Baayen et al., 2008; Dixon, 2008; T. F. Jaeger, 2008). First, aggregation of data within items and participants is unnecessary for mixed models. All of the data can be used and the need to conduct separate participant and item analyses is eliminated, simplifying interpretation and the inherent problems of this approach (R. H. Baayen, 2004; H. Clark, 1973; Raaijmakers et al., 1999). Second, missing data at random can be handled easily, and the relative contribution of participants (e.g., more accurate participants, more response time data) can be weighted effectively to provide more robust estimates of behavioural effects. Third, the mixed effects framework can be use flexibly for continuous (e.g., response times) and categorical outcomes (e.g., accuracy) and predictors, which make them versatile and powerful tools. Finally, mixed effects models are designed to take into account the hierarchical structure, or clustering of the data. Experiments are special cases of clustered data, where trials are nested within participants, who are nested within specific conditions. The ability to specify levels of data within these models allows for identification and quantification of random variability that is accounted for to produce more accurate effect size

estimates compared to ANOVA. On this latter point, we know that individual response profiles vary considerably as a function of task and stimulus characteristics (Kliegl et al., 2010), and that individual responses to tDCS are affected by myriad (Krause & Cohen Kadosh, 2014). With this knowledge, multi-level analyses are the ideal tool for analysis of experimental effects and individual differences in tDCS studies.

8.2 Utility of tDCS

On first consideration, there is great promise for a technique like tDCS. It is relatively cheap and portable, with an excellent safety profile (Woods et al., 2016) and critically it provides a method for direct manipulation of brain function. However, the application of non-invasive brain stimulation techniques is not straightforward or simple in practice, and our understanding of the physiological effects of electrical currents on the brain is limited at best (Bonaiuto & Bestmann, 2015). As a rehabilitative tool, tDCS may demonstrate considerable efficacy as an adjunct to therapy in a variety of domains, including rehabilitation of language deficits following stroke (Cappon et al., 2016; Crinion, 2016). However, there is a considerable gap between the number of therapy studies and the number of basic science studies that aim to understand the factors that influence performance.

Despite methodological improvements in stimulus and task controls, the tDCS effects in this thesis are somewhat inconsistent with previous work. The null finding in study one provides little hint that tDCS had any observable effect on healthy participants' naming performance consistent with a recent meta-analysis on the subject (Simonsmeier et al., 2018; Westwood & Romani, 2017). Although interesting, the interaction effects in study three were weak and require replication before any definitive conclusions can be made about mechanisms. The relative pattern of failure and success across these studies may be partially consistent with a recent meta-analysis that reported effect sizes three times larger in learning tasks relative to performance tasks, like naming (Simonsmeier et al., 2018). However, on

closer inspection the average Cohen's *d* effect size of .712 for learning studies reported by Simonsmeier et al. (2018) is likely to be over-inflated, and potentially driven by one or two unusually large effect sizes, in small samples. A number of other meta-analyses have been published examining the effects of tDCS on cognition and language performance specifically but conclusions vary on the relative efficacy of tDCS to enhance cognition (Horvath et al., 2015b; Mancuso et al., 2016; Medina & Cason, 2017; A. R. Price et al., 2015; Simonsmeier et al., 2018; Westwood & Romani, 2017). The only consistent conclusion from meta-analytic studies to date is the methodological heterogeneity between studies, rendering the interpretation of any meta-analytic findings at this stage quite difficult.

A further important point to note is that there were inconsistent effects of sham across the two tDCS studies. Blinding was not intact in study one, but it was in study two. This may be due to the differences in current density, as it can be more difficult to blind participants to higher current amplitudes (Ambrus et al., 2010, 2012; Kessler et al., 2012b; Russo et al., 2013; Wallace et al., 2016) although recent studies refute the claim that blinding is intact even at 1mA (Greinacher et al., 2019; Turi et al., 2019). Alternatively, the success of blinding in study three may also have been due to the elimination of any rumination time as the task lasted for the full length of the stimulation period, whereas the naming task began after 10 minutes of stimulation in study one. Effective sham protocols and the potential application of active control sites are warranted in future (Fonteneau et al., 2019).

Finally, it is clear that most tDCS studies are under-powered to detect subtler effects (Mancuso et al., 2016; Medina & Cason, 2017; Minarik et al., 2016) including those reported in this thesis. Medina and Cason (2017) reported that tDCS studies in the cognitive domain have only 14% power on average. For more complex designs, achieving appropriate power for interactions is challenging at best (e.g., Brysbaert & Stevens, 2018), even if the smallest

effect of interest can be computed with any degree of insight (Anvari & Lakens, 2019; Cribbie et al., 2019, p. 7; Gruijters & Peters, 2019; Lakens, 2017).

In sum, the findings from two studies are not sufficient, in and of themselves, to question the efficacy of tDCS. Considering recent criticism of overblown claims surrounding tDCS effects, questionable replicability of individual studies amongst healthy adults, and inconsistent meta-analytic findings, one must question the practical benefit of tDCS as a basic research instrument but to abandon the technique as the observations are being made would be overzealous.

8.3 Future directions

There are myriad factors that need to be considered when designing and evaluating tDCS studies. Much of this work has yet to be carried out. On reflection, the designs of the studies reported on in this thesis are likely too complex and attempt to test too many novel hypotheses. Future studies would require considerable re-development to examine specific effects in isolation, as a larger body of exploratory and explanatory work. For example, the learning paradigm could have been adapted to examine the role of the phonological similarity of pseudowords in interaction with tDCS or language ability alone, or study three could have adopted just non cognates from a real foreign language to examine generalisability of learning effects under tDCS in relation to the work of Flöel et al. (2008). To some extent, the studies in this thesis extend too far beyond what has been tested thus far in the language domain. However, the questions raised in review of the literature and development of the design of studies in this thesis are important. Issues around replicability and generalisation of tDCS effects within studies and to different sets and types of stimuli (Study 1, Study 3) are paramount if we are to understand the limits and applications of this technique. Moreover, attempts to include moderators in tDCS and language studies in general are limited but they

are sorely needed if we are to understand how language, learning and memory are influenced by individual differences, and the subsequent impact on tDCS effects.

Most studies in the language domain examine changes in single sessions and this is important in terms of efficiency of time and resources. Multiple stimulation sessions may be one way of maximising these effects, but this requires additional resources. Multi-session protocols based on our current knowledge raise ethical questions around potential long-term synaptic changes that may benefit task performance on the one-hand, whilst impairing performance in some other domain (Brem et al., 2013; Harty et al., 2016). A more nuanced approach might involve application of high definition tDCS techniques in combination with individualised current modelling (Datta, 2012; Dmochowski et al., 2013; Edwards et al., 2013; Kuo et al., 2013; Nikolin et al., 2015). Two recent studies have utilised HD-tDCS for the enhancement of word learning in older adults, for example (Perceval et al., 2017a; Perceval, Martin, Copland, Laine, & Meinzer, 2017b) but inclusion of additional moderators increases the complexity of the studies. Although it may be possible to appropriately power studies to detect small-moderate effects in simple studies with few comparisons, examining more complex interactions, or moderating effects, may require larger scale, multi-site collaborations to understand the limits and necessary conditions of effects with any degree of certainty.

Another potential approach would be to develop hypotheses around the use of other electrical waveforms, like transcranial alternating current (tACS) or transcranial random noise stimulation (tRNS). The non-specific, constant current provided with tDCS may be insufficient to result in robust shifts in membrane thresholds because of strong homeostatic regulation in healthy adults (Paulus, 2011). Specific attempts to modulate key oscillatory frequencies may be a positive step forward. (Zoefel & Davis, 2017) discuss the potential application of tACS to the modulation of speech comprehension. Slow-wave (4-10Hz) tACS

applied to left temporal-parietal regions may enhance speech perception abilities and this may make this frequency domain a target for enhancement of word learning in future. Furthermore, a number of studies have reported improved cognitive performance with tRNS (Pasqualotto et al., 2015; Penton et al., 2017; Snowball et al., 2013; Terney et al., 2008)A number of studies have shown that tRNS may modulate gamma-band activity (Rufener et al., 2016; Van Doren et al., 2014). Differences in gamma-band peaks can differentiate between object and action naming in the LOC, with concurrent changes in relative glutamate concentrations (Lally et al., 2013), which may highlight the gamma-band frequency as a target for improved naming or object processing performance.

8.4 Concluding Remarks

In conclusion, this thesis presents a considered and methodological approach to examining tDCS effects on language processing in healthy adults. The effects of tDCS were mixed and subtle at best but we present a framework that may improve our understanding in future. Consideration of participant, task and stimulus-level characteristics are likely to enhance our understanding of the limits and extent of electrical stimulation techniques for the study of cognition. Acknowledgment of general issues that plague the field around study design, adequate blinding, power, and replication, coupled with appropriate statistical analyses will undoubtedly enhance future work.

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Appendix A

Table A1

LMM for Log-Transformed Response Times with All Four Phonological Similarity Bands for

Chapter 6

	LMM: log(RT)			
	β	95 % CI	*t*	*p*
Intercept	6.565	6.54,6.59	616.70	**<.001**
Language Status [Monolingual, Bilingual]	-0.005	-0.04,0.03	-0.30	.781
log(Block)	-0.067	-0.08,-0.06	-17.50	**<.001**
Phonological Similarity				
Band 1 vs. Band 2 [PSim1]	-0.014	-0.02,-0.00	-2.85	**.004**
Band 2 vs. Band 3 [PSim2]	-0.028	-0.04,-0.02	-5.72	**<.001**
Band 3 vs. Band 4 [PSim3]	-0.03	-0.05,-0.01	-2.92	**.003**
Trial Type [Foil, Target]	-0.008	-0.02,0.01	-1.01	.313
Language Status:log(Block)	0.035	0.02,0.05	4.68	**<.001**
Language Status: Phonological Similarity				
Language Status: PSim1	-0.017	-0.03,0.00	-1.85	.065
Language Status: PSim2	0.007	-0.01,0.03	0.80	.425
Language Status: PSim3	-0.035	-0.08,0.01	-1.67	.096
log(Block): Phonological Similarity				
log(Block):PSim1	0.011	0.00,0.02	2.79	**.005**
log(Block):PSim2	-0.003	-0.01,0.00	-0.76	.448
log(Block):PSim3	0.002	-0.02,0.02	0.22	.824
Language Status:Trial Type	0.01	-0.02,0.04	0.62	.532
log(Block):Trial Type	-0.025	-0.03,-0.02	-7.47	**<.001**
Trial Type:Phonological Similarity				
Trial Type: PSim1	-0.028	-0.05,-0.01	-3.08	**.003**
Trial Type: PSim2	-0.066	-0.08,-0.05	-7.07	**<.001**
Trial Type: PSim3	-0.043	-0.08,-0.00	-2.31	**.033**
Language Status:log(Block):Phonological Similarity				
Language Status:log(Block):PSim1	0.009	-0.00,0.02	1.29	.198
Language Status:log(Block):PSim2	-0.003	-0.02,0.01	-0.40	.689
Language Status:log(Block):PSim3	0.025	-0.01,0.06	1.42	.156
Language Status:log(Block):Trial Type	-0.018	-0.03,-0.00	-2.70	**.007**
Language Status: Phonological Similarity: TrialType				
Language Status:PSim1:TrialType	-0.018	-0.05,0.02	-1.02	.305
Language Status:PSim2:TrialType	0.019	-0.01,0.05	1.11	.267
Language Status:PSim3:TrialType	0.057	-0.02,0.14	1.41	.158
log(Block):Phonological Similarity:Trial Type				
log(Block):PSim1:Trial Type	0.02	0.00,0.04	2.54	**.011**
log(Block):PSim2:Trial Type	-0.008	-0.02,0.01	-0.99	.324
log(Block):PSim3:Trial Type	0.005	-0.03,0.04	0.28	.781
Language Status:log(Block):Phonological Similarity:Trial Type				
Language Status:log(Block):PSim1:Trial Type	0.01	-0.02,0.04	0.64	.521
Language Status:log(Block):PSim2:Trial Type	-0.005	-0.03,0.02	-0.32	.745
Language Status:log(Block):PSim3:Trial Type	-0.055	-0.12,0.01	-1.58	.115

Table A1 continued

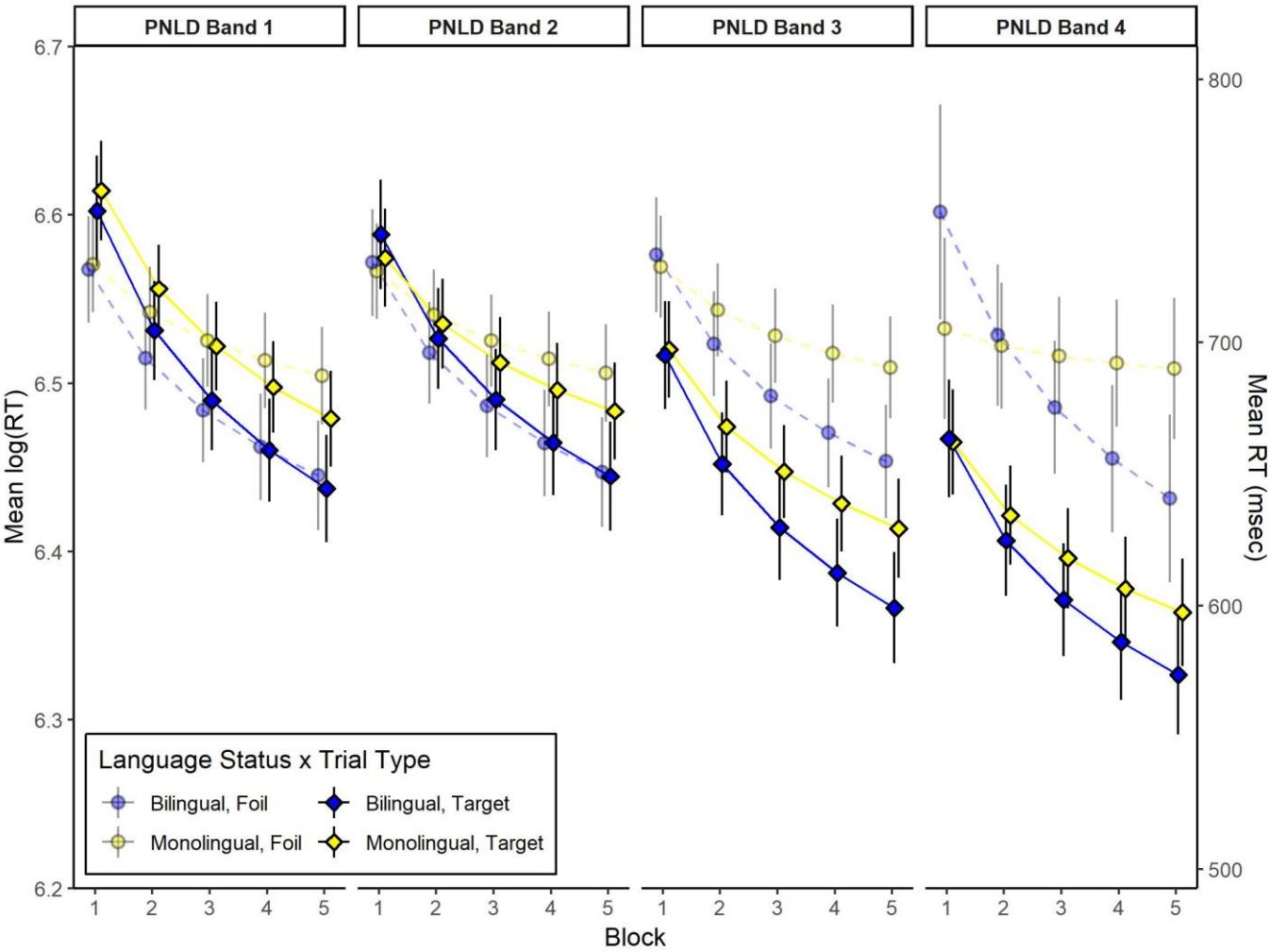| Random Effects	
σ^2	0.025
$\tau_{00, \text{Participants}}$	0.014
$\tau_{00, \text{Concepts}}$	0.004
ρ_{01}	-0.155
$N_{\text{Participants}}$	63
N_{Concepts}	60
$ICC_{\text{Participants}}$	0.332
ICC_{Concepts}	0.095
Observations	49466
R^2 / Ω_0^2	.318 / .318
AIC	-41685.705

Figure A1. Mean log response latencies and 95% CIs as a function of Block and Language Status, panelled by phonological similarity bands. Exponentiated response latencies in milliseconds for reference on right axis.

Appendix B

Table B1

GLMM for Translation Accuracy with More Lenient Coding Scheme

	Lenient			
	lnOR	*95% CI*	*z*	*p*
(Intercept)	0.35	-0.15 – 0.85	1.371	.171
Language Status	-0.17	-0.61 – 0.27	-0.744	.457
Session: Immediate vs. Day After [Session1]	-0.19	-0.32 – -0.05	-2.745	**.006**
Session: Day After vs. Follow-up [Session2]	-0.17	-0.37 – 0.03	-1.662	.096
Phonological Similairty: Band 1 vs. Band 2 [PSim1]	0.33	-1.00 – 1.65	0.483	.629
Phonological Similairty: Band 2 vs. Band 3 [PSim2]	1.35	0.14 – 2.55	2.188	**.029**
Phonological Similairty: Band 3 vs. Band 4 [PSim3]	1.80	0.42 – 3.18	2.554	**.011**
Language Status:Session1	0.06	-0.20 – 0.32	0.441	.659
Language Status:Session2	0.33	-0.07 – 0.73	1.626	.104
Language Status:PSim1	0.29	-0.39 – 0.98	0.833	.405
Language Status:PSim2	-0.49	-1.09 – 0.12	-1.582	.114
Language Status:PSim3	-0.11	-0.86 – 0.63	-0.295	.768
Session1:PSim1	-0.14	-0.38 – 0.09	-1.196	.232
Session2:PSim1	0.12	-0.15 – 0.38	0.874	.382
Session1:PSim2	-0.06	-0.28 – 0.17	-0.484	.629
Session2:PSim2	0.26	0.02 – 0.51	2.103	**.035**
Session1:PSim3	-0.19	-0.48 – 0.11	-1.235	.217
Session2:PSim3	-0.09	-0.40 – 0.21	-0.587	.557
Language Status:Session1:PSim1	0.37	-0.09 – 0.83	1.559	.119
Language Status:Session2:PSim1	0.00	-0.52 – 0.52	0.004	.997
Language Status:Session1:PSim2	-0.44	-0.88 – 0.00	-1.95	.051
Language Status:Session2:PSim2	-0.01	-0.49 – 0.48	-0.027	.979
Language Status:Session1:PSim3	0.29	-0.28 – 0.87	1.003	.316
Language Status:Session2:PSim3	-0.12	-0.73 – 0.48	-0.404	.686
Random Parts				
τ_{00}, Participants			0.605	
τ_{00}, Concepts			3.274	
ρ_{01}			0.368	
NParticipants			63	
NConcepts			60	
ICCParticipants			0.084	
ICCConcepts			0.457	
Observations			20868	
Tjur's D			0.437	
AIC			19052.544	
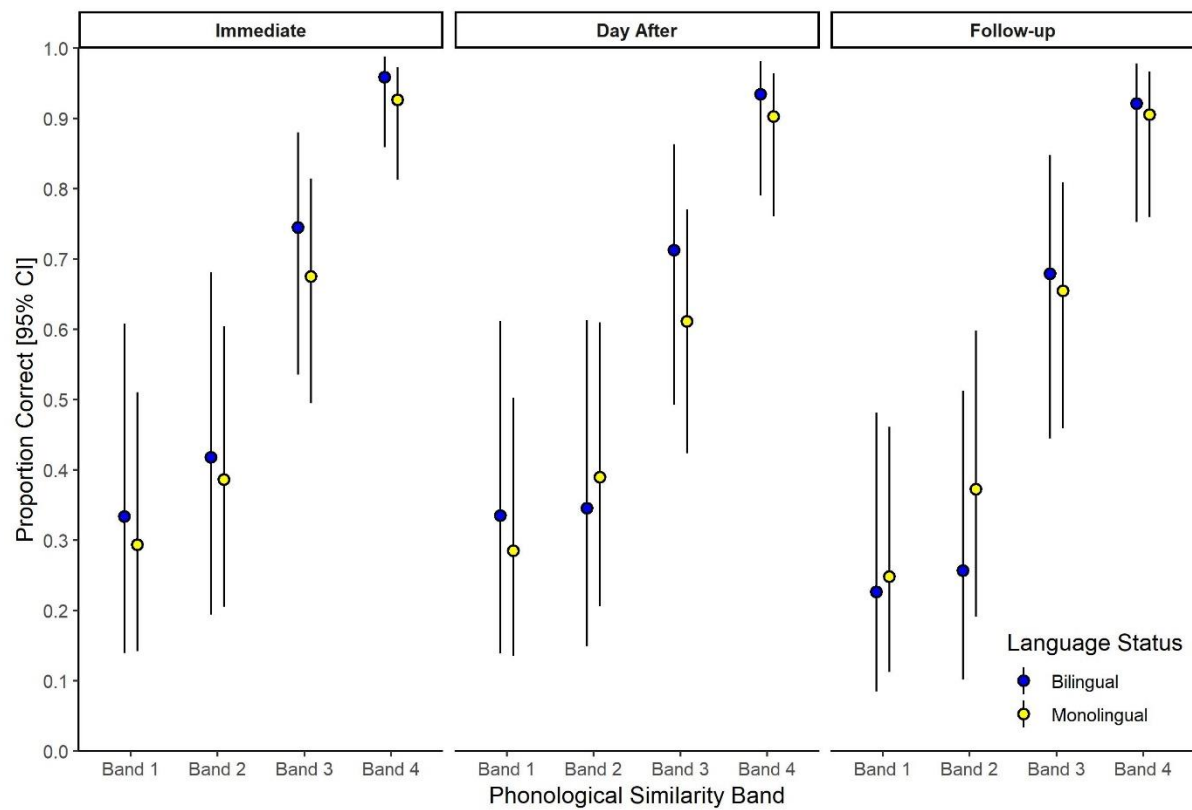
Figure B1. Proportion correct translation responses and 95% CIs separated by phonological

similarity band, Session and Language Status with a more lenient coding scheme. Results are

largely similar to stricter coding scheme.

Appendix C

Table C1.

LMM for Log-Transformed Response Times with All Four Phonological Similarity Bands for

Chapter 7 tDCS Study

	Response Latencies			
	B	*CI*	*t*	*p*
(Intercept)	6.519	6.48 – 6.55	357.979	**<.001**
Stimulation (Sham, Active)	-0.009	-0.03 – 0.02	-0.661	.514
log(Block)	-0.059	-0.07 – -0.05	-9.002	**<.001**
Phonological Similarity				
Band 1 vs. Band 2 [PSim1]	-0.013	-0.03 – 0.00	-1.741	.082
Band 2 vs. Band 3 [PSim 2]	-0.037	-0.05 – -0.02	-5.013	**<.001**
Band 3 vs. Band 4 [PSim 3]	-0.039	-0.07 – -0.01	-2.506	**.012**
Trial Type (Foil, Target)	-0.006	-0.02 – 0.01	-1.047	.295
Stimulation:log(Block)	0.000	-0.02 – 0.02	0.02	.984
Stimulation:PSim1	0.001	-0.02 – 0.03	0.053	.958
Stimulation:PSim2	0.016	-0.01 – 0.04	1.28	.201
Stimulation:PSim3	-0.049	-0.11 – 0.01	-1.646	.100
log(Block):PSim1	0.010	-0.00 – 0.02	1.898	.058
log(Block):PSim2	0.000	-0.01 – 0.01	0.065	.948
log(Block):PSim3	-0.004	-0.03 – 0.02	-0.291	.771
Stimulation:Trial Type	0.015	-0.01 – 0.04	1.309	.190
log(Block):Trial Type	-0.025	-0.03 – -0.02	-5.061	**<.001**
PSim1:Trial Type	-0.025	-0.05 – 0.00	-1.838	.066
PSim2:Trial Type	-0.068	-0.09 – -0.04	-5.213	**<.001**
PSim3:Trial Type	-0.038	-0.10 – 0.02	-1.284	.199
Stimulation:log(Block):PSim1	-0.007	-0.03 – 0.01	-0.662	.508
Stimulation:log(Block):PSim2	-0.009	-0.03 – 0.01	-0.862	.389
Stimulation:log(Block):PSim3	0.031	-0.02 – 0.08	1.23	.219
Stimulation:log(Block):Trial Type	-0.017	-0.04 – 0.00	-1.78	.075
Stimulation:PSim1:Trial Type	0.003	-0.05 – 0.05	0.108	.914
Stimulation:PSim2:Trial Type	-0.039	-0.09 – 0.01	-1.569	.117
Stimulation:PSim3:Trial Type	0.032	-0.08 – 0.15	0.548	.584
log(Block):PSim1:Trial Type	0.019	-0.00 – 0.04	1.738	.082
log(Block):PSim2:Trial Type	-0.005	-0.03 – 0.02	-0.479	.632
log(Block):PSim3:Trial Type	0.012	-0.04 – 0.06	0.502	.616
Stimulation:log(Block):PSim1:Trial Type	0.000	-0.04 – 0.04	0.021	.983
Stimulation:log(Block):PSim2:Trial Type	0.044	0.00 – 0.09	2.064	**.039**
Stimulation:log(Block):PSim3:Trial Type	-0.036	-0.13 – 0.06	-0.734	.463

Table C1 continued

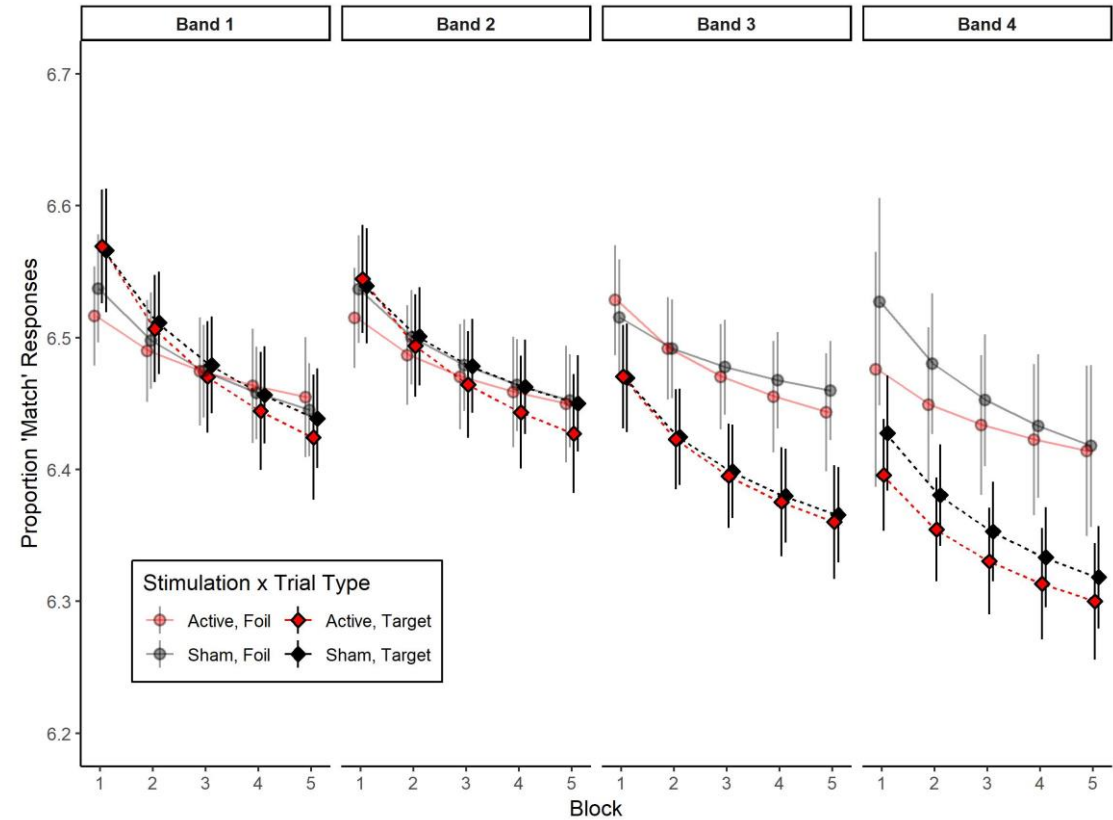| **Random Effects**	
σ^2	0.025
τ_{00}, Concepts	0.004
τ_{00}, Participants	0.024
ρ_{01}	-0.67
NConcepts	60
NParticipants	32
ICCConcepts	0.079
ICCParticipants	0.45
Observations	25345
R2	.386 / .386
AIC	-21021.527

Figure C1. Log-transformed response latencies [95% CI] and exponentiated response times (right axis), as a function of Block and Trial type, panelled by Phonological Similarity Bands and Stimulation Type. Foils reflect correct rejections.