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The Influence of Long-Term Linguistic Knowledge on Verbal Short-Term Memory in Adults With and Without Dyslexia: Behavioural and Electrophysiological Insights

A thesis by
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Submitted in accordance with the requirements for the degree of Doctor of Philosophy

York St. John University
School of Education, Language, and Psychology

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Abstract

This thesis analysed the impact of lexical-semantic knowledge on verbal short-term memory (vSTM) in individuals with and without dyslexia. Given that dyslexic individuals generally exhibit phonological difficulties, this investigation sought to understand whether they leverage their lexical-semantic knowledge as a compensatory mechanism in vSTM, mirroring tendencies observed in reading tasks. Chapters 2 and 3 studied the impact of newly acquired linguistic knowledge on vSTM. Chapter 2 found that newly gained phonological-lexical knowledge boosted nonword recall, but further semantic associations offered no extra benefits, particularly for dyslexic participants. In contrast, Chapter 3, after strengthening the training methodology, found that both phonological familiarity and semantic training improved recall, benefiting dyslexic and non-dyslexic participants alike. Chapter 4 investigated the impact of associating nonwords with high or low-imageability words, although the results did not show substantial differentiation for any participants. Chapter 5 pivoted to scrutinise the role of well-integrated lexical-semantic representations in vSTM, showing that both imageability and semantic relatedness enhanced recall, even at a rapid presentation rate, implying these semantic influences were largely automatic. Here, individuals with weaker phonological skills benefitted more from word imageability under faster presentations. Chapter 6 replicated the beneficial effect of semantic coherence on vSTM performance, revealing similarly enhanced accuracy in both groups, although a differing pattern of errors indicated dyslexic participants may use different recall strategies. Throughout the thesis, experiments have replicated the supportive effects of phonological-lexical representations and added benefits of established semantic knowledge in vSTM and, through similar levels of performance, demonstrated that these sources of support likely have an important contribution to maintaining functional STM capacity in dyslexia; although the efficacy and degree to which they can boost vSTM performance may be limited. These insights offer a valuable foundation for future research into lexical-semantic mechanisms underpinning language processing in dyslexia.

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Abbreviations

ISR = Immediate Serial Recall
vSTM = Verbal Short-Term Memory
LTM = Long-Term Memory
SBH = Semantic Binding Hypothesis
PSH = Primary Systems Hypothesis
SD = Semantic Dementia
SEM = Semantically trained items
FAM = Phonologically familiarised items
RT = Reaction Time
ERP = Event Related Potential
MMN = Mismatched Negativity
EMG = Electromyography
IMG = Imageability
SD = Standard Deviation
BF = Bayesian Factor
CAP = Item recalled in any serial position
CIP = Item recalled in the correct serial position
ORD = Order error, item recalled in the incorrect serial position
RECOMB = Recombination
MIG = Migration
ACC = Accuracy

Chapter 1. Theoretical Background

1.1 Introduction

Our capacity to retain words for brief periods is influenced by several factors. Imagine a scenario where you and a friend are on a grocery run for a dinner party, without the option to jot down a list. You are in charge of eggs, milk, cheese, butter, custard, and cream, while your friend is tasked with procuring candles, salmon, napkins, oil, bread, and carrots. Upon returning home, there is a high probability that you will have successfully procured all your items, while your friend may have forgotten a few. This discrepancy can be attributed to your ability to cluster your grocery list into a single semantic category - dairy. Your friend, on the other hand, did not have this luxury. This exemplifies how pre-existing knowledge (in this case, the semantic category "dairy") can enhance our short-term memory functions (remembering the shopping list).

The role of long-term stored information in immediate recall was largely ignored or discounted in initial models of verbal short-term memory (vSTM) in the 1960's and 1970's, which envisaged long-term memory (LTM) and short-term memory as two distinct systems operating independently (e.g., Baddeley & Hitch, 1974). However, one consequence of this perspective was to overlook the notion that vSTM predominantly functions to store language-related representations, thus necessitating probable interactions with the phonological, lexical, and semantic representations of the language system. In this context, three decades later, long-term and short-term memory interactions became a central research interest, giving rise to a multitude of studies and resulting models, going from envisaging indirectly related systems (e.g., Baddeley, 2000), to models that consider vSTM as a temporary activation of the language system (e.g., N. Martin & Saffran, 1992). In parallel, neuropsychological studies in language processing and reading proposed that a range of language tasks including reading, repetition and vSTM stem from the language system (Patterson & Lambon Ralph, 1999; Plaut et al., 1996; Seidenberg & McClelland, 1989), without the need for additional systems (e.g., dual-route models of reading, Coltheart et al., 1993). More specifically, this view holds that phonological and semantic primary systems underlie language processing, and that the semantic system can compensate for weak phonological processing (e.g., Crisp & Lambon Ralph, 2006). Here, we can appreciate analogies between memory and language research areas, with competing accounts considering that vSTM is either supported by a unique language system, or by dedicated structures.

The aim of this thesis is to contribute to unifying these research areas by examining whether the influence of long-term linguistic (semantic) knowledge on verbal short-term memory is modulated by general phonological abilities, with a particular interest in those with developmental dyslexia. Thereby, in a series of studies (Chapters 2 to 6), the role of linguistic knowledge in vSTM will be investigated in adults with a diagnosis of developmental dyslexia expected to show phonological weaknesses. Assuming that vSTM arises from the language system, it would be anticipated that individuals with developmental dyslexia would show stronger sensitivity to lexical-semantic properties compared to non-dyslexic individuals. This stems from the idea that their challenges with phonological processing could lead to a greater reliance on lexical-semantic cues to bolster their vSTM performance. Additionally, considering that various kinds of semantic knowledge may link to distinct structures within long-term memory — each likely to have unique effects — it is essential to explore a wide array of semantic information types. This would enable us to discern if certain types of semantic information have a greater influence on short-term recall than others.

In this first chapter, after describing characteristics of short-term and long-term memory through the review of classical models and a discussion of the dichotomy between STM and LTM, an overview will be given of the theoretical literature coupled with empirical data examining vSTM and LTM interactions in language processing and vSTM. I will then outline relevant theories of dyslexia as well as data evidencing semantic compensation, before defining the objectives of the thesis along with adopted experimental and statistical approaches.

1.2 Definitions of memory systems

Short-term and long-term memory distinction

In his quest to unravel the core characteristics of memory, Ebbinghaus (1885) pioneered a unique theoretical approach to memory research via his explorations and observations in verbal memory. He conducted experiments by testing his own capacity to remember lists composed of nonsense syllables. Ebbinghaus (1885) discovered that the first attempt to recall a list of syllables always resulted in an average recall performance of seven syllables, and that repeated presentation of the list increased this recall performance. This observation resulted in the distinction between two systems: one rapid memory system with limited storage, and another system that appears to be illimited. These systems were later referred to as "primary memory" and "secondary memory" by James (1890).

In the 1960s, with the emergence of cognitive psychology, researchers re-examined the concept of memory (e.g., Conrad, 1964; Peterson & Peterson, 1959). A myriad of studies confirmed the proposed differentiation between primary and secondary memory. For example, one line of evidence was based on free recall tasks, in which participants recall a list of words independently of their presentation order. In this task, Glanzer and Cunitz (1966) showed that in immediate recall, the first and last items were better remembered than items in the middle of the list (these effects are termed primacy and recency effects, respectively). In delayed recall (i.e., when participants perform a task such as mental arithmetic during a short retention interval), the recency effect disappeared while the primacy effect was preserved. On this basis, it was considered that the last items of the list were stored in short-term memory and that the first items were stored in long-term memory, thus establishing a dissociation between STM and LTM.

One of the most influential memory models that posits a distinction between LTM and STM is the modal model proposed by Atkinson and Shiffrin (1968). This model is composed of three systems: the sensory register, the short-term memory store, and the long-term memory store. It assumes that information is first processed in a sensory register, and then some of this information is transmitted to the short-term memory store, which in turn transmits the information to a long-term store. Initially, information from the world is processed in parallel through different sensory registers, and the information is stored according to its dimension (auditory, visual, etc.) in the corresponding sensory register for a very short period of time (typically one or two seconds). These registers then provide information to the second component of the model, the short-term store, but not all information that arrives in the sensory register passes into the short-term store because of its limited capacity. Thus, a selection process occurs by matching with information stored in the long-term memory store, which leads to the recoding of information, no longer dependent on modality.

In the short-term store of this model, coding is mainly phonological, and the storage duration is relatively short (up to 30 seconds). The short-term memory store not only stores information, but it is also responsible for several processes such as rehearsal, allowing for the transfer to the long-term memory store, the coding of information, including semantic coding, and retrieval strategies. The short-term store plays a crucial role in this model since information must pass through it before reaching the long-term register. Rehearsal in the short-term store strengthens the trace that is then transferred to the long-term store. Therefore, the long-term store is constructed from the information stored and repeated in the short-term store. It is not limited in duration or storage capacity, and the information is coded semantically.

A central point of this model concerns the transfer of information, which can occur from the short-term to the long-term store, and vice versa. Atkinson and Shiffrin (1968) suggest that the information contained in the long-term store must be moved to the short-term store for the processing of new information entering the system. Characteristics of long-term stored information are compared to those of the new information, and this comparison allows the selection of the information from the sensory register that will be transferred to the short-term store.

This detailed model explains many effects observed in the literature. It accounts for the recency effect, which comes from short-term memory, and the primacy effect, which comes from long-term memory after repetition. However, it was challenged by Craik and Lockhart (1972) who suggested that the deeper the information is encoded, the more permanent the memory trace; implicating that time in the store is less important than the operation performed on the information. A further argument in favour of the separation and independence of the two systems, STM and LTM, has been highlighted by neuropsychology studies. Atkinson and Shiffrin's modal model (1968) considers that information must necessarily pass through the short-term store before being stored in long-term memory. However, it cannot explain the inverse dissociation presented by Shallice and Warrington's (1970) patient who had a deficit in STM (span reduced to 2 or

3 digits, no recency effect) and preserved LTM. According to the modal model, a deficit in STM should have led to a deficit in LTM and other cognitive domains, as passing through this register is a fundamental step for learning and reasoning.

The modal model of Atkinson and Shiffrin (1968), which cannot explain the case of this patient was thus abandoned. The main criticism of this model concerns the relationship it assumes between STM and LTM: information must necessarily pass through STM and be repeated before it can be stored in LTM. Based on these criticisms and other experimental data, Baddeley and Hitch (1974) developed a new theoretical model in which STM and LTM have no relationship.

Working memory and short-term memory, similar yet different

Despite the refutation of Atkinson and Shiffrin's (1968) model based on neuropsychology findings, the modal model has had a great influence on the development of subsequent models. Atkinson and Shiffrin (1968) consider the unit of short-term storage as a temporary working memory that allows for the completion of cognitive tasks. The concept of STM, designed as a unitary system, is thus abandoned and incorporated into a more complex framework, working memory, which stores and processes information. The completion of cognitive tasks, such as problem solving, requires the maintenance of information for a certain amount of time, but also its processing and coordination. Mental calculation is a very representative task of the function of working memory. Thus, researchers have integrated processes that allow for the manipulation of information, since simple storage is not enough for most tasks.

Working memory involves the maintenance and processing of information (e.g., remembering numbers in order to complete a mental operation). A representative measure of working memory is the backwards digit span, in which participants attempt to recall a sequence of digits in the reverse order in which it was presented. This test involves both the retention of information and the processing which requires the modification of the order of the digits.

It should be noted that the concept of STM is still used for tasks requiring information storage only. STM involves only passively maintaining information without any processing or transformation of this information. Short-term memory refers to the ability to hold a limited amount of information (7 ± 2 units of information according to G. A. Miller, 1956; but see Cowan, 2001, for a revision of this number down to 4 chunks) for a short duration (e.g., maintaining a phone number until it can be written down). This system is commonly measured by the digit span task in which the participant must remember a sequence of digits in the order in which it was presented. The digit span represents the longest correct sequence reproduced. Another typical measure of STM is the immediate serial recall (ISR) task in which participants hear a list of items that they attempt to recall in the same serial order.

This thesis will primarily concentrate on aspects of STM, and I predominantly employed immediate serial recall tasks, which require storage of information without active processing. Nevertheless, given that STM is nested within the broader concept of working memory, it is imporant to provide a description of the key working memory models.

The working memory model from Baddeley and Hitch (1974)

One prevailing theory of working memory, built on Atkinson and Shiffrin (1968), was proposed by Baddeley (1986; Baddeley & Hitch, 1974). It posits a multicomponent system with a central executive component which is an attentional system that processes and manipulates information, and supervises two slave systems: the phonological loop and the visuo-spatial sketchpad, which temporary store phonological and visuo-spatial information, respectively (see **Figure 1.1**). The phonological loop will be described below, since its capacity is measured by memory span tasks involving verbal material used in the present research.

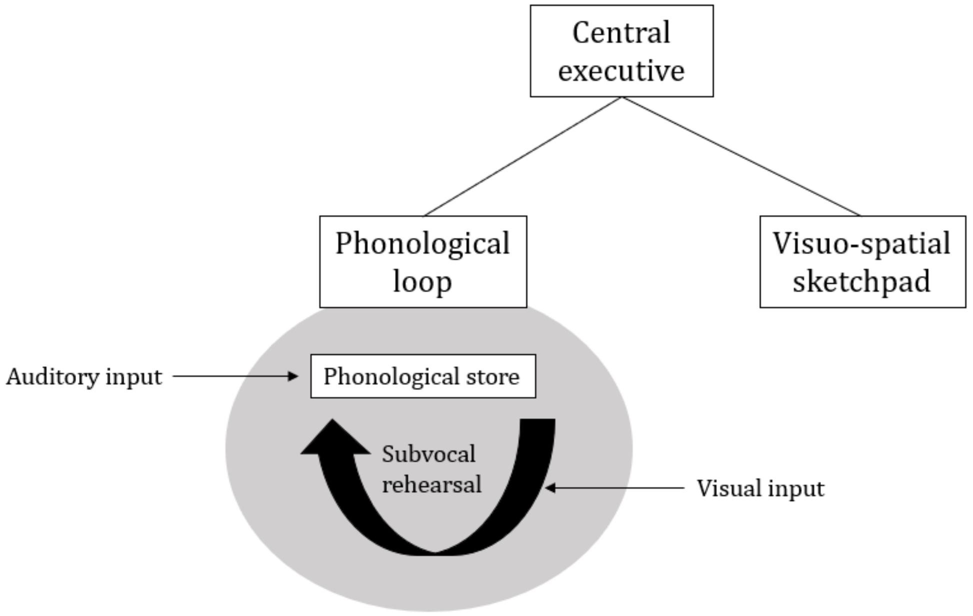

Figure 1.1. *Schematic of Baddeley and Hitch's (1974) working memory model.*

The phonological loop, as described, consists of a phonological store and an articulatory control process, and is specialised in maintaining phonologically coded verbal information. Auditorily presented information access the phonological store and is maintained for one and a half to two seconds. After this delay, these memory traces start to decay. However, they can be reintroduced in the phonological store through subvocal articulation, which relies on inner speech. This process is not only capable of refreshing the memory trace, but it also allows for the conversion of visually presented material into a phonological code.

The phonological store accounts for the phonological similarity effect whereby phonologically similar items are less likely to be correctly recalled than phonologically dissimilar items (Baddeley, 1966). The phonological similarity effect is explained by the fact that the phonological store relies on a phonological code, thus, in lists of phonologically similar items, codes are less distinct from each other, which leads to confusion. Another effect informing conception of the phonological loop is the recall advantage for short words over long words, known as the word length effect (Baddeley et al., 1975, 1984). This can be explained by a longer rehearsal time of long words, which allows for the decay of the memory trace of other words that cannot be repeated. It is assumed that the articulatory loop's function is to maintain the elements in the phonological store through subvocal rehearsal, hence, the faster this process, the greater the memory span.

Further evidence for the phonological loop arises from the articulatory suppression effect. When participants are asked to repeat a meaningless sequence of sounds, such as "ba ba ba ba" or words like "the the the the”, when encoding items, their memory span decreases, and it removes the word length effect (Baddeley et al., 1975). This effect is independent of the elements being pronounced and arises from the fact that the articulation of the repeated sound or word dominates the subvocal articulatory rehearsal process, thereby preventing its use, either to maintain elements located in the phonological store or to convert visual elements into phonological code (Baddeley et al., 1984).

This model allows for the description of working memory processes involved in immediate serial recall. However, it does not take into account a possible relationship between working memory and long-term memory and has been confronted with data that suggest a contribution of long-term memory in memory span tasks, which in simple form, it cannot readily explain. For instance, in studies controlling for phonological-lexical neighbourhood size – referring to the number of acoustically similar neighbours a word possesses (e.g., neighbours of the word *heat* would be *seat, beat, feet, meat, neat, sheet*, etc.), stored in long-term memory – the word length effect vanishes (Jalbert, Neath, & Surprenant, 2011; Jalbert, Neath, Bireta, et al., 2011). That is, when participants attempt to recall lists of short (e.g., *cat*) and long (e.g., *banana*) words that have the same neighbourhood size, short words do not benefit from a recall advantage (Jalbert, Neath, Bireta, et al., 2011, Experiments 3 and 4). Thus, rather than length affecting rehearsing time as predicted by the working memory model (Baddeley & Hitch, 1974), it seems that linguistic properties of the words are better suited to explain the word length effect, suggesting that long-term stored information interacts with working memory.

Baddeley (2000) later amended his working memory model to allow for interactions between working memory and linguistic long-term memory by adding an episodic buffer which combines information from different stores and codes. The episodic buffer serves as a bridge connecting short-term phonological store, visuo-spatial store and long-term memory, that is accessed through conscious awareness. This updated version of the working memory model will be reviewed in section 1.5. While Baddeley's model provides a valuable framework for understanding working memory, other researchers have proposed alternative concepts, such as the model developed by Cowan (1999), which will be discussed in the following section.

Embedded processes model of working memory: Cowan (1999)

In contrast with Baddeley and Hitch's (1974) model, embedded process models such as the one from Cowan (1995, 1999, 2001) consider that working memory is embedded within long-term memory, with attentional focus playing a central part. According to this model, working memory stems from an activated section of long-term memory within which a subset of long-term memory representations is placed under the focus of attention and awareness.

The focus of attention can be seen as the equivalent of short-term memory and can hold four activated representations (termed chunks). The focus of attention can move from one activated long-term memory representation to another under the influence of voluntary processing, or through attentional capture via external stimuli. By virtue of the focus of attention, activated information can be maintained indefinitely, unless representations are excessively degraded since activated memory is subject to decay. Contrary to Baddeley’s (1974) model, embedded processes can explain the influence of long-term memory on working memory, such as the correlation between vocabulary acquisition and working memory, without needing additional systems.

Cowan's embedded process model of memory is not constrained to the domain of working memory, but rather extends its applicability across various language domains. This aligns with the concept of primary systems view (Patterson et al., 1999, detailed in section 1.3), which posits that language abilities are grounded in a set of fundamental, domain-specific systems. This raises important questions regarding whether functions of memory are domain-specific or general. One of the key propositions of Cowan's model is that it does not need a separate mechanism for short-term and long-term memory. Instead, these two facets of memory are considered to be intimately linked and not distinctly separate mechanisms. This idea is critical for this thesis and bears significant implications for understanding the interplay between short-term memory, long-term memory, and language abilities more broadly. The relationship between the two types of memory becomes particularly relevant when considering individuals with poorer phonological abilities, such as those with dyslexia. The interconnected nature of short-term and long-term memory systems as proposed by Cowan's model may provide an interesting perspective on how to address the difficulties faced by individuals with dyslexia. Rather than treating STM deficits as isolated problems, it might be more productive to approach them in the context of a broader, unified memory system. This integrated perspective could potentially pave the way for more effective strategies for supporting individuals with dyslexia and other similar language-related difficulties.

Working memory and word learning

Further evidence of the relationship between working memory and long-term memory can be observed in language acquisition and processing. Associations between verbal STM measures and vocabulary were first demonstrated in a longitudinal study by Gathercole and Baddeley (1989), who showed that nonword repetition performance (phonological short-term memory) at 4 years old predicted vocabulary skills a year later, and that repetition performance correlated with vocabulary score at the same age. A strong involvement of the phonological loop in vocabulary acquisition was suggested by studies examining nonword repetition in children with specific language impairments[1] (Gathercole & Baddeley, 1990). The phonological loop maintains the representation of a new word to optimise its learning. Therefore, a low capacity leads to poor language development, suggesting that vSTM abilities affect long-term memory. Similar results were found in foreign-language learning, whereby the repetition of unfamiliar foreign words can predict the acquisition of new vocabulary in language learning (Service, 1992). It has also been demonstrated that the disruption of subvocal rehearsal in the phonological loop by articulatory suppression or syllabic length impacts the learning of nonwords, without affecting the learning of real words, indicating that the phonological

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[1] Nonword repetition deficit characterises children with specific language impairments (e.g., Conti-ramsden et al., 2001; Gray, 2003; Stothard et al., 1998).

loop is involved in novel word learning, particularly when lexical support is unavailable (Papagno et al., 1989; Papagno & Vallar, 1992).

This correlation between nonword repetition and vocabulary acquisition can be explained by the fact that there are no stored lexical-semantic representations of nonwords and unknown new vocabulary in the mental lexicon on which individuals can rely. In contrast, reliance on lexical representation seems to occur in immediate recall of known words, benefitting from existing representations in long-term memory (Hulme et al., 1991). In Gathercole (1995), the use of nonwords with varying degrees of wordlikeness (i.e., high wordlike items resemble existing words such as *voltularity*) demonstrated that repetition of high wordlike nonwords is partly based on long-term lexical knowledge (see also Edwards et al., 2004). Indeed, wordlike nonwords are composed of phonological segments shared with familiar words, serving as a support in vSTM. These are examples of long-term memory influences on vSTM.

Together these studies reveal a reciprocal relationship between vocabulary and working memory. They show that the phonological loop contributes to language acquisition and, conversely, that long-term representations are used to strengthen vSTM. Another line of evidence in favour of a close link between long-term memory and vSTM lies in research investigating the role of long-term linguistic representations in immediate recall. This link is generally examined through the use of information stored in semantic memory and will be detailed in section 1.4. Semantic properties involved in studies investigating semantic effects on vSTM are typically related to taxonomy (i.e., words belonging to the same semantic category), or concreteness/imageability (i.e., the extent to which a word gives rise to a mental image). The relationship between language and memory calls for a more nuanced understanding of semantic memory. In essence, semantic representations - the meanings we ascribe to words and concepts - are fundamental to how we understand and use language. These semantic representations serve as an archive from which vSTM can draw upon during the recall process. The specific structure and organisation of this semantic information within LTM can greatly influence the efficiency and effectiveness of this recall. As such, investigating the nature of these semantic representations in vSTM can provide insights into our understanding of memory processing. Thus, the following section aims to define semantic memory and different types of representations that it contained, since the nature of semantic properties changes depending on the material used, which can lead to varied effects in vSTM.

Semantic memory

Upon investigating memory, Tulving (1972) proposed two types of long-term explicit memory with *a priori* unlimited capacity: episodic memory, storing autobiographic events associated with their context of encoding (e.g., my last birthday party); and semantic memory which stores general knowledge about the world, symbols and concepts, independently of its context of encoding (Patterson et al., 2007). Research over the last decades has focused on the nature, organisation, and neural architecture of semantic memory, giving rise to a number of approaches including network-based models, distributional models, and feature-based models (for a review, see Kumar, 2021). It should be noted that semantic concepts can be linked taxonomically (i.e., based on shared features such as *cat* and *dog*), or thematically (i.e., based on experience and the co-occurrence of events such as *cake* and *candle*).

Collins and Quillian (1969), conceptualised semantic memory as a taxonomically and hierarchically organised network with categories (or nodes) and properties defining each category (e.g., *has skin*). It is assumed that categories are organised hierarchically with three levels: supersets (e.g., *animal*), category names (e.g., *fish*), and subsets (e.g., *salmon* or *shark*), which all have pointers to characterising properties. For example, properties of the concept “salmon” are ”is pink”, and “swims upstream to lay eggs”. More general properties are stored in superset concepts such as “has fins” stored within the “fish” concept, and “breathes” stored in the concept “animal”.

In this model, each concept is equidistant to the category it pertains to, which does not account for typicality effects, whereby individuals are faster to verify *a robin is a bird* compared to *an ostrich is a bird*, suggesting that some members of a category are more typical than others (Rips et al., 1973; Rosch & Mervis, 1975). In Collins and Quillian's (1969) model, reaction time to verify typical and atypical members of a category should be the same, since their semantic distance to the category is identical. Collins and Loftus (1975) revised the initial model and proposed a non-hierarchical spreading activation model of semantic memory that considers semantic distance. According to this model, relationships between words correspond to the frequency in which they are used conjointly, implying that this model comprises taxonomic and thematic relationships between words. When a concept is activated, it becomes the starting point of the spreading activation within the network. Spreading is done progressively, activating the concepts in an automatic way, so that the activation of one concept facilitates the activation of nearby concepts. Evidence supporting this model stems from semantic priming effects in lexical decision tasks. That is, individuals are faster at deciding whether an item presented is a word or a nonword if a semantically related prime (e.g., shirt-*dress*) is presented before the target, compared to an unrelated prime (e.g., *road*-*dress*), suggesting that semantic representations are automatically retrieved (Hutchison, 2003; Meyer & Schvaneveldt, 1971; Neely, 1977).

In light of spreading activation models, the activation of a word triggers rapid activation of nearby words that share semantic characteristics (Lambon Ralph et al., 2017; Patterson et al., 2007). This can account for semantic similarity (i.e., taxonomic relationship) and semantic relatedness (i.e., thematic relationship) effects in vSTM, whereby memory span is better for semantically related words than for unrelated words, because semantically similar/related items belong to the same semantic space (Calfee & Peterson, 1968; Crosson et al., 1999; Crowder, 1979; Monnier et al., 2011; Neale & Tehan, 2007; Poirier & Saint-Aubin, 1995; Saint-Aubin et al., 2005; Saint-Aubin & Poirier, 1999b; Tse, 2009; Tse et al., 2011; Wetherick, 1975).

Studies have coupled neuroimaging and behavioural data to explain semantic processing, and more particularly the concreteness effects by which concrete words are processed more effectively than abstract concepts. This effect has been observed in neuropsychological studies with patients with aphasia[2] and deep dyslexia[3] (Barry & Gerhand, 2003; Berndt et al., 2002; Franklin, 1989; Kiran et al., 2009; Newton & Barry, 1997), and semantic dementia[4] (Jefferies, Patterson, et al., 2009); but also in healthy individuals in various language tasks including comprehension, lexical decision, word recognition and recall (de Groot, 1989; C. T. James, 1975; Kroll & Merves, 1986; Paivio, 1991). Two prominent theories have been developed to explain concreteness effects: the dual-coding theory (Paivio, 1991) and the context availability theory (Schwanenflugel, 1991; Schwanenflugel & Shoben, 1983). According to the dual-coding account, concrete words are processed more efficiently because they are represented by verbal and perceptual codes, while abstract words are represented by verbal codes only. Hence, concrete words would recruit left hemisphere language regions and additional visual representations within the right hemisphere, engendering their processing advantage over abstract words (Binder et al., 2005; Sabsevitz et al., 2005).

Conversely, the context availability account (Schwanenflugel, 1991; Schwanenflugel & Shoben, 1983) considers that the advantage for concrete words comes from the greater amount of available contextual information associated with them. Contextual information

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[2] Aphasia is an acquired language impairment caused by brain damage. A distinction between fluent and non-fluent aphasia is commonly made:

Fluent aphasia (also known as Wernicke's aphasia or receptive aphasia) is characterised by the ability to produce speech that is fluent and grammatically correct, but may contain errors in word choice and syntax. Individuals with fluent aphasia often have difficulty with language comprehension and may produce speech that lacks meaning or is nonsensical.

Non-fluent aphasia (also known as Broca's aphasia or expressive aphasia) is characterised by difficulty with speech production. Individuals with non-fluent aphasia may struggle to articulate words, produce complete sentences, and form grammatically correct language. Language comprehension is usually relatively preserved or only mildly affected.

[3] Deep dyslexia is an acquired reading deficit that is characterised by severe reading difficulties and a range of associated language and cognitive deficits. It is typically caused by brain damage resulting from stroke, traumatic brain injury, or degenerative neurological conditions such as Alzheimer's disease. People with deep dyslexia often exhibit a pattern of errors that involves producing semantically related errors when reading aloud. For example, they may read "chair" as "table" or "book" as "reading". Additionally, they may have difficulty with reading abstract words, function words, and nonwords.

[4] Semantic dementia is a neurodegenerative condition that primarily affects semantic memory. The progressive atrophy of the temporal neocortex leads to the loss of semantic knowledge and conceptual understanding of words, objects, and concepts, resulting in difficulty with naming objects, understanding the meaning of words, and recognising familiar faces and objects.

refers to settings and situations in which a word is encountered, as well as semantic knowledge proper to each person, which is richer for concrete than for abstract concepts. This theory is supported by studies showing that when abstract and concrete words are presented in the meaningful context with sufficient verbal information, there is no concreteness effects (Schwanenflugel et al., 1988; Schwanenflugel & Stowe, 1989). Thus, the dual-coding and context availability theories both assume that concrete concepts are supported by richer semantic associations, but while the dual-coding account suggests that concrete words benefit from multi-modal processing in both hemispheres, the context availability theory proposes that abstract and concrete words are processed in a single verbal system situated in the left hemisphere, with concrete words having a greater activation due to the availability of contextual information.

As a consequence of inconsistent findings from studies attempting to verify dual-coding and context availability theories (Binder et al., 2005; Fiebach & Friederici, 2003; Grossman et al., 2002; Jessen et al., 2000; Kiehl et al., 1999; Noppeney & Price, 2004; Perani et al., 1999; Pexman et al., 2007; Sabsevitz et al., 2005), contemporary accounts such as the modified embodiment theory (Binder & Desai, 2011) consider that semantic memory includes supramodal and modality-specific representations. In this model, supramodal representations are supported by convergence zones located in the inferior parietal and temporal cortex in the sensory-motor and emotional systems, and the development of modality-specific representations is influenced by perceptual experiences, which eventually integrate with higher-level convergence zones to bind the different modality representations together. Concept representations are processed differently depending on their familiarity and the available perceptual and contextual information. Therefore, concrete words are likely to generate more activity than abstract words due to their abundant sensory-motor representations and richer conceptual characteristics, and activation of concrete words is distributed over distinct neural networks (Roxbury et al., 2014).

In studies examining the effect of semantic representations on language tasks, concreteness and imageability are variables that are often used interchangeably. However, it should be noted that imageability and concreteness variables are highly related, but they contribute to slightly different aspects of semantic representations.

While most concrete words are generally considered to be imageable, abstract words tend to have more variable imageability ratings (Barber et al., 2013; Kousta et al., 2011). Imageability refers to sensory (primarily visual, but can also be tactile, olfactive, etc.) information attached to a word, whereas concreteness indexes either spatiotemporally situated and independent of language concepts for concrete words or non-spatiotemporally situated and dependent on language for abstract concepts (Hale, 1988; Kousta et al., 2011). Despite these differences, both concrete and highly imageable are associated with more stable and richer semantic representations, which underlies their processing advantage over abstract and low imageability words.

Following this non-exhaustive exploration of semantic memory, it is essential to direct our attention to another crucial aspect of our cognitive system, namely the phonological domain. Specifically, if vSTM reflects an activation of long-term memory, it is imperative to comprehend how this system operates and how its various levels of representation, particularly the phonological and semantic systems, interact.

1.3 Interactions between phonology and semantics across language domains

Connectionists ‘triangle’ models of single-word processing (Plaut, 1997; Plaut et al., 1996a; Seidenberg & McClelland, 1989) consider that reading – as well as other language tasks – is achieved through interactions between semantic, phonological, and orthographic systems (see **Figure 1.2**). The underlying idea of this account is that reading is underpinned by language systems involved in and developed over the course of other language activities, rather than by neural mechanisms dedicated to reading, since reading is a relatively recently developed skill. According to this view, semantic representations support the processing of both familiar and unfamiliar words, but to varying degrees. For example, in a seminal study, Strain et al. (1995) examined semantic-phonological interactions in a phonological task (i.e., single-word naming task with manipulation of spelling-to-sound regularity and imageability of word targets) and found stronger imageability effects for irregular words compared to regular words. This suggests that if translation between orthography and phonology is less efficient (i.e., when reading irregular words), processing is more strongly modulated by semantic representations (see also Cortese et al., 1997; Shibahara et al., 2003; Strain et al., 2002; Strain & Herdman, 1999).

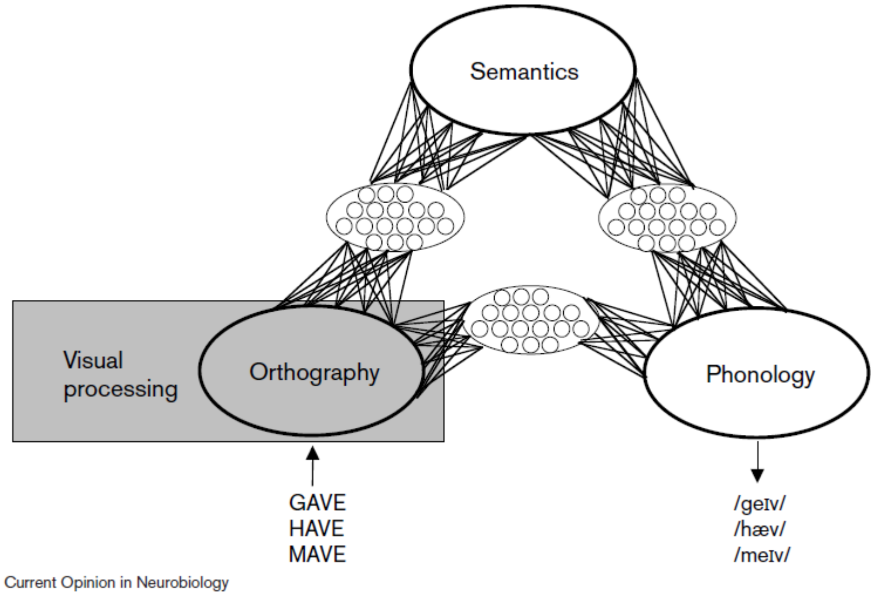

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Figure 1.2*. Primary Systems Hypothesis connectionist framework of word processing based on Plaut (1997) and Seidenberg and McClelland (1989), taken from Patterson and Lambon Ralph (1999).*

Accordingly, Plaut et al. (1996) proposed that graded division of labour between semantic and phonological language systems varies depending on the nature of the processed item, and that neither of these systems alone is fully proficient, since both must collaborate to facilitate proficient reading of both words and nonwords. This perspective differs from dual-route models of reading (Coltheart et al., 2001) positing that reading is achieved through two distinct neural pathways or routes involved in reading: the lexical and the sublexical route. The lexical route involves the direct recognition of words based on their orthographic appearance, used for reading familiar words that are stored in the reader's mental lexicon. The sublexical route contains grapheme-to-phoneme correspondence rules, used for reading unfamiliar words or nonwords, which are not stored in the mental lexicon. Thus, according to dual-route models, semantic knowledge mediates reading through the lexical route only. Neuropsychological studies have provided strong evidence in favour of triangle models (e.g., Woollams et al., 2007).

One such study is that of Patterson and Lambon Ralph (1999) who suggested that different types of acquired alexia can be explained by the disruption of semantic, phonological, or visual processing. For example, phonological alexia, an acquired disorder of reading with a substantial nonword and unfamiliar word reading deficit, can be explained through this framework as a low activation of the phonological system, due to a phonological deficit, resulting in difficulties in reading nonwords; since they do not benefit from semantic support provided by the semantic system. Semantic effects in reading, such as the effect of imageability, seem to increase when the phonological system is affected, suggesting that the semantic system can compensate for phonological deficits. This idea was called the "primary systems hypothesis", considering that language arises from domain-general interactions between semantic and phonological representations (Lambon Ralph et al., 2002; Patterson & Lambon Ralph, 1999).

In addition, the primary systems hypothesis predicts that, because reading arises from the language system, reading impairment should be coupled with other language difficulties (Patterson et al., 2006). This prediction was verified by Crisp and Lambon Ralph (2006) with a case series study examining characteristics of individuals with phonological and deep dyslexia and evaluating their phonological and semantic processing abilities. Crisp and Lambon Ralph (2006) found that, in all cases, reading deficits were associated with phonological impairments, and that participants with better semantic skills (measured with a synonym judgement task) showed increased lexicality effects (i.e., better reading performance for words over nonwords). Moreover, imageability effects in reading (i.e., better reading performance for high- over low-imageability words) were more substantial when participants' phonological skills were weak, and less important with better semantic skills. These correlations indicate a strong interaction between phonological and semantic representations, the status of primary systems is reflected by lexical and semantic effects in reading (Crisp et al., 2011; Crisp & Lambon Ralph, 2006). Strong interactions between primary systems were also found in speech production with aphasic patients, whereby the degree of anomia (i.e., word-finding difficulties) was predicted by the integrity of their semantic and phonological representations (Lambon Ralph et al., 2000, 2002).

Relatedly, in repetition tasks (in which the visual system of triangle models would be replaced by auditory processing), weakness in the phonological system seems to boost semantic effects, as suggested by stronger reliance on lexical-semantic variables such as imageability and lexicality in phonologically impaired patients with aphasia (Jefferies, Crisp, & Lambon Ralph, 2006). The reverse pattern has been observed in patients with semantic dementia who show weaker effects of semantic variables (Jefferies, Crisp, & Lambon Ralph, 2006). Comparably, patients with deep dysphasia (i.e., patients with aphasia showing severe phonological impairments) show important effects of semantic variables in repetition coupled with the inability to repeat nonwords, suggesting that semantic representations play a compensatory role in repetition (Jefferies et al., 2007; Katz & Goodglass, 1990; Majerus et al., 2001; N. Martin & Saffran, 1992; Valdois et al., 1995; Wilshire & Fisher, 2004).

Such interactions have also been found in neuropsychological studies assessing vSTM. For example, Verhaegen et al. (2013) examined vSTM performance of two patients with aphasia, one with phonological deficits and the other with lexical-semantic impairment. They found that phonological impairments resulted in increased frequency effects (i.e., better recall for frequent over infrequent words, reflecting lexical-semantic knowledge) in ISR, and that lexical-semantic deficits increased phonotactic frequency[5] effects (i.e., better memory span for high- compared to low-phonotactic-frequency nonwords). These results indicate that, as predicted by the primary systems hypothesis (Patterson & Lambon Ralph, 1999; Plaut, 1997), interactions between semantic and phonological systems underpin a range of linguistic tasks (e.g., reading and repetition), but they also seem to occur in short-term memory. This is important since it suggests that vSTM does not rely on a dedicated, task-specific system, but that, instead, vSTM could be supported by the language system.

A trade-off between semantic and phonological systems in reading has been found in language unimpaired participants. That is, when the phonological system is put under pressure, such as when reading inconsistent spelling-to-sound words (e.g., *pint* or *bear*), semantic effects are more pronounced than when reading consistent words (e.g., *mint* or *dear*) (Cortese et al., 1997; Hoffman et al., 2015; Shibahara et al., 2003; Taylor et al., 2015;

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[5] The frequency of occurrence of phoneme combinations in a certain language - such as the diphone [ka] is more common in English than [aʊ].

Woollams, 2005). Increased semantic reliance in reading seems to be associated with poorer phonological skills, as evidenced by Strain and Herdman's (1999) study, showing that performance at tasks measuring phonological skills predicted the magnitude of the imageability effect (see Woollams et al., 2016, for similar results).

Despite scarcer evidence for similar effects (i.e., stronger reliance on semantic representations when phonological skills are weak) in vSTM in language unimpaired individuals, Ueno et al. (2014) developed a neuroanatomically constrained computational model of the primary systems account. This model includes the ventral (semantic) and dorsal (phonological) language pathways, which was combined with human experiments examining the impact of semantic representations on accent processing. More precisely, Japanese words with correct and incorrect pitch accents, and with low or high imageability ratings were used in single word repetition and ISR tasks. Incorrect pitch accent is intended to mirror the manipulation of inconsistent orthography to phonology translation in reading, since it changes the phonological consistency/typicality of these words. Neurocomputational results showed greater involvement of the ventral pathway – implicated in semantic maintenance – in atypical pitch accent words repetition, as predicted by the division of labour between phonological and semantic systems of the primary systems hypothesis. In addition, human experiments revealed that the influence of imageability in immediate serial recall performance was more substantial when repeating words with incorrect accent compared to words with correct accents, supporting results from neurocomputational modelling (see also Woollams et al., 2018).

The aforementioned literature indicates that when the phonological system is stressed or weak, the semantic system is likely to play a supportive role, even when semantic representations are not *a priori* vital to complete the task. Evidence indicates that this division of labour between systems is generalisable across language (e.g., Ueno et al., 2014) and language domains (Savill et al., 2019). It thus seems that primary systems responsible for language production and comprehension may represent vSTM, without the need for additional systems such as the phonological loop (Baddeley & Hitch, 1974). This concept of the interactions between the phonological and semantic systems and their roles in situations of stress or weakness within the phonological system is a significant theme that I will address in the research presented in this thesis.

A recent study by Savill et al. (2019) motivates some of the key questions in the present research: They tested predictions of the primary systems hypothesis on language unimpaired adult participants across language tasks, including vSTM. Namely, they examined whether the language system supporting reading, vSTM, and repetition evidenced comparable semantic influences as indexed by effects of imageability. These effects were manipulated across word items in speeded reading aloud, immediate serial recall and speeded spoken repetition tasks. Additionally, the study investigated whether phonological processing performance was associated with these semantic effects. They found increased imageability effects (i.e., faster and more accurate performance for high compared to low imageability words) in all tasks and, in reading and vSTM tasks, these effects were more pronounced in those with poorer phonological performance (as indexed by nonword performance in each task and psychometric performance on phonological tasks); indicating that underlying phonological skills predict the degree of reliance on lexical-semantic variables across multiple tasks. These individual differences in linguistic task data were compatible with primary systems dynamics being evidenced in healthy individuals in a similar way to what is observed in patients with phonological deficits; particularly in challenging conditions (e.g., under time pressure, or with above span lists lengths in ISR).

This pattern of semantic effects scaling with (weaker) phonological function is explored further by extending to test participants with developmental dyslexia in the experimental work of this thesis. The rationale behind this decision lies in the perspective dyslexic individuals can offer into vSTM. Dyslexia is typically characterised by phonological difficulties, thus, by observing how these individuals perform in vSTM tasks, we can further assess the potential interdependence between phonological and semantic systems, potentially leading to a more nuanced understanding of language processing in both healthy and dyslexic individuals.

Research related to phonological-semantic interactions in language processing and investigations examining semantic support of the phonological trace in vSTM are usually segregated. However, the presented evidence indicates that vSTM and language functions may be closely related, since abilities in one language domain may influence the other, including vSTM. This is important as it would be at odds with traditional views of working memory positing that the short-term memory store is separated from long-term memory (e.g., Baddeley & Hitch, 1974), and echoes views that consider vSTM as an activated section of long-term memory (e.g., Cowan, 1999) discussed in the previous section. These contrasting theoretical conceptions underlie numerous models developed or modified to account for the involvement of long-term memory in vSTM, which will be discussed in section 1.5. However, I will first review studies examining the contribution of long-term linguistic representations in vSTM, followed by a discussion of the theoretical concepts derived from these findings.

1.4 Contributions of long-term linguistic knowledge to verbal short-term memory

The historical argument in favour of a dichotomy between STM and long-term memory, stemming from studies examining the nature of phonological similarity effects in STM, is that information is coded differently for these two systems: STM depends on phonological coding (Baddeley, 1966; Conrad, 1964; Conrad & Hull, 1964; Kintsch & Buschke, 1969; Wickelgren, Wayne, 1965), whereas long-term memory codes information semantically (Baddeley & Dale, 1966). This suggests that while phonology plays an important role in vSTM, semantic knowledge would not – or only minimally – contribute to vSTM. Although many studies support this distinction related to information coding, others, that show effects of long-term linguistic representations in vSTM, do not support this hypothesis.

This section will present a review of neuropsychological and behavioural evidence demonstrating the influence of different types of linguistic knowledge on vSTM, typically examined via immediate serial recall tasks (ISR), in which participants hear a list of items that they attempt to recall in the same serial order. It should be noted that immediate serial recall tasks reflect the recall of the items themselves and their order.

Evidence for the contribution of linguistic knowledge in verbal short-term memory

Linguistic knowledge operates at various levels, each possibly impacting vSTM. These levels include sublexical (phonological), lexical, and super-lexical (semantic) dimensions. The sublexical level refers to phonological segments of words which provide foundational structures upon which lexical (the whole word form) and semantic (the meaning of the word) knowledge are built.

Sublexical contribution to verbal short-term memory

At the sublexical level, phonological knowledge seems to play an important role in vSTM, as suggested by the phonotactic frequency effect (Gathercole, Frankish, et al., 1999). That is, the frequency of occurrence of phoneme combinations in a certain language - such as the diphone [ka] is more common in English than [aʊ] - is known to impact the ease with which we process nonwords (Vitevitch et al., 1997); but also ISR performance with a recall advantage for nonwords containing high phonotactic frequency over low phonotactic frequency (Gathercole, Frankish, et al., 1999; Majerus & Van der Linden, 2003). Phonological long-term memory effects like these suggest that sublexical knowledge influences vSTM performance. However, when controlling for lexical neighbourhood size which refers to the number of acoustically similar neighbours a word has (e.g., phonological neighbours of the word *heat* would be *seat, beat, feet, meat, neat, sheet,…*), Roodenrys and Hinton (2002) found no phonotactic frequency effect in ISR performance, suggesting that the phonotactic frequency effect found in Gathercole, Frankish, et al. (1999) could have been driven by lexical representations rather than by phonological knowledge. In response to Roodenrys and Hinton (2002), Thorn and Frankish (2005) showed that biphone frequency considerably impacted nonword recall when neighbourhood size was controlled, and that neighbourhood size had a significant effect on nonword recall when biphone frequency was controlled. This implies that long-term knowledge contributions to nonword recall are not solely lexical but derive from both lexical and phonotactic knowledge.

Lexical contribution to verbal short-term memory

Compelling evidence for the influence of linguistic knowledge on vSTM comes from reliably better recall of words over nonwords in ISR; the so-called lexicality effect (Brener, 1940; Hulme et al., 1991, 1995; Jefferies, Frankish, & Lambon, 2006; Roodenrys & Hulme, 1993; Savill et al., 2015, 2017; J. E. Turner et al., 2000). For instance, Hulme et al. (1991) showed that at similar speech rate, there was a consistent recall advantage for words over nonwords, which they interpreted as reflecting the contribution of the articulatory loop (i.e., items requiring more time to articulate take longer to rehearse, Baddeley et al., 1975; Ellis & Hennelly, 1980), and the contribution of lexical knowledge on vSTM.

Another line of evidence for long-term lexical effects on vSTM stems from studies that first familiarised participants to the phonological form of nonwords to then compare their recall to relatively new nonwords (Hulme et al., 1995; Savill et al., 2015, 2017). Hulme et al. (1995) compared recall performance of words and nonwords, before and after learning through repetition of their phonological form. They observed a boost in the span of nonwords post training, which was more substantial than the increase in recall performance for the words. These results were interpreted as a sign of the construction of phonological representations in long-term memory, which are responsible for the recall difference between words and trained nonwords, rather than semantic representations. In Savill et al. (2015), participants were auditorily presented with nonwords paired with either a clear or a blurred image, prior to an ISR task that comprised phonologically familiar nonwords and new, unfamiliar nonwords. Results showed an increased recall performance for phonologically familiar nonwords compared to new nonwords, suggesting that newly acquired phonological-lexical representations influence vSTM even when items are meaningless.

The impact of lexical representations has also been observed via effects of lexical frequency (Gregg et al., 1989; Hulme et al., 1997; Kowialiewski & Majerus, 2018; Majerus & Van der Linden, 2003; Poirier et al., 1996; Roodenrys et al., 2000, 2010; Tehan & Humphreys, 1988; Watkins & Watkins, 1977). The frequency with which we use words (e.g., the word *night* is used more frequently than the word *strew* according to SUBTLEX-UK Zipf frequencies, van Heuven et al., 2014) influences vSTM performance, as suggested by increased memory span for high frequency compared to low frequency words. This effect can be interpreted as illustrating the contribution of lexical representations to vSTM (Watkins & Watkins, 1977).

The recall advantage for high over low frequency words can be explained by a greater familiarity with the items, making them more accessible than low frequency words. It can also be that more semantic information is attached to these words compared to low frequency words whose meaning may be more abstract, or even unknown by the participants. Lexicality and frequency effects seem to represent the involvement of lexical representations on vSTM, but they may also reflect the contribution of semantic knowledge.

Semantic contribution to verbal short-term memory

Neuropsychological and neuroimaging evidence for the involvement of semantic knowledge in verbal short-term memory

A line of evidence for the contribution of semantic knowledge to vSTM comes from patients with specific phonological or semantic impairments. Semantic dementia, a variant of primary progressive aphasia, is a neurodegenerative disorder associated with progressive atrophy of the left anterior temporal neocortex, resulting in semantic memory loss (Lambon Ralph et al., 2017). Several studies showed that patients with semantic dementia are better at recalling words whose meaning they still know than recalling words whose meaning they no longer know (Hodges et al., 1994; Jefferies, Jones, et al., 2004; Knott et al., 1997; Majerus et al., 2007; Patterson et al., 1994). Such results suggests that poorer performance in vSTM stems from a deficit in the semantic system in LTM, and thus, that semantic knowledge is an important determinant of performance in vSTM.

Patterson et al. (1994) administered an immediate serial recall task to three patients with semantic dementia. The lists tested comprised words whose meaning was intact, and words with degraded semantic representation, which were individually selected depending on each participant. Patients demonstrated an overall recall advantage for known over phonologically familiar but semantically degraded words, and, importantly, authors noticed an increase of phoneme level ordering errors for the semantically degraded items. That is, when recalling semantically degraded words, participants tended to recombine phonological elements of the words (e.g., *cap*, *dog* was recalled *dap, cog*), these types of errors are also known as phonological migrations, and are similar to those made by healthy participants serial recall of nonwords (Jefferies, Frankish, & Lambon, 2006). Patterson et al.'s results were interpreted as reflecting the deterioration of semantic knowledge, which, when preserved, enables the selection and maintenance of correct phonological configuration in vSTM, leading Patterson et al. (1994) to formulate the 'semantic binding hypothesis' whereby verbal STM function directly emerges from activation of language and associated long-term representations. This hypothesis will be further discussed in section 1.5. It could be argued that the semantic advantage found in Patterson et al. (1994) could be a result of higher lexical frequency for words whose meaning was intact, since word frequency strongly influences the degradation of semantic representations in patients with aphasia (Papagno et al., 2013). However, similar semantic effects were found with words matched for frequency (Knott et al., 1997). Yet individual language experiences mean frequency might still be a contributing factor.

A potential approach to distinguish exposure effects involves training with nonwords, ensuring perfectly matched exposure both with and without semantic information (Savill et al., 2017). This technique was employed in Chapters 2 and 3 of this thesis, which will be elaborated upon in the following sections. In addition, Majerus et al. (2007) examined short-term recall of item information (i.e., items recalled correctly in any position within the list) and serial order information (i.e., item recalled in the correct serial position) in patients with semantic dementia and found they have poor lexico-semantic information recall (low recall of words) in immediate serial recall, while recall of phonological information is preserved (normal recall of nonwords). Authors specified patients have a greater number of word item errors but fewer order errors than control participants. This suggests that semantic knowledge has a positive effect on item identity, but not on order information, indicating that the language system is a crucial determinant of vSTM performance.

Neuroimaging studies offer further evidence for the role of linguistic knowledge in vSTM. Using positron emission tomography, Collette et al. (2001) evaluated whether differences in brain activation appear for the recall of items that have no representation in long-term memory (nonwords), compared to words. They showed that, in vSTM tasks, words' processing, as opposed to nonwords, leads to increased activity in the middle temporal gyrus, which, coupled with the anterior inferior frontal cortex, has been shown to form the ventral pathway involved in lexical-semantic processing (Friederici & Gierhan, 2013; Hickok & Poeppel, 2007; Lambon Ralph et al., 2017). Converging evidence stems from the use of inhibitory transcranial magnetic stimulation (TMS). Savill et al. (2018) found that when the left anterior middle temporal gyrus (ATL) - a region linked to semantic processing - was stimulated, there was a disruption in the recall of words but not nonwords, showing tight links between the lexical-semantic network and vSTM function (see also Kowialiewski et al., 2020).

Evidence for the contribution of lexical-semantic knowledge in vSTM in healthy participants

The extent to which long-term lexical-semantic representations contribute to vSTM is a matter of debate, due to vSTM tasks being more susceptible to acoustic than to semantic variables (Baddeley, 1966, 1972; Baddeley & Dale, 1966; Shulman, 1971). For example, a plethora of studies have found an effect of semantic similarity, whereby recall of semantically similar items (e.g., *moon, sky, blue,* cloud) is better than recall of semantically dissimilar words (e.g., *car, dog, heat, aim*) (Calfee & Peterson, 1968; Huttenlocher & Newcombe, 1976; Kowialiewski & Majerus, 2018; Poirier & Saint-Aubin, 1995; Saint-Aubin et al., 2005; Saint-Aubin & Poirier, 1999b; Wetherick, 1975). However, Baddeley (1966) showed that the impact of phonological similarity on vSTM was more substantial than semantic similarity in a serial recall task. Interestingly, it seems that semantic similarity can have a detrimental effect on order recall (i.e., items recalled in the correct serial position), but Baddeley's study did not measure recall performance for item identity (i.e., items recalled in any serial position). Lexical-semantic effects in vSTM are commonly thought to impact recall of item identity with no or minimal influence on the maintenance of order information (Allen & Hulme, 2006; Campoy et al., 2015; Hulme et al., 1997; Poirier & Saint-Aubin, 1995; Romani et al., 2008; Saint-Aubin & Poirier, 1999b; Tse & Altarriba, 2007; Walker & Hulme, 1999). Crowder (1979) pointed that the recall benefit of using semantically associated words varied based on the scoring method employed, which could explain why recall performance did not benefit from semantic similarity in Baddeley (1966). In fact, several studies have found increased recall of item identity for lists containing semantically related compared to unrelated words, corroborating the hypothesis according to which semantic similarity benefits recall of item information (Monnier et al., 2011; Neale & Tehan, 2007; Poirier & Saint-Aubin, 1995; Tse, 2009; Tse et al., 2011).

Poirier and Saint-Aubin (1995) observed semantic similarity effects when they compared recall accuracy of lists of semantically related to lists of semantically unrelated words. Words from the semantically related lists were randomly arranged to form semantically unrelated lists. Since items were the same in the semantically related and unrelated lists, superior recall for lists whose words were semantically associated can only be explained by semantic knowledge, indicating that semantic representations play a significant role in vSTM. Importantly, recall advantage for semantically similar words could stem from inter-item associations of shared semantic features (see Dell et al., 1997). Another semantic variable that can be used to observe the influence of semantic representations on vSTM is imageability, which taps on individual item-level semantic knowledge.

Word's imageability refers to the extent to which a word gives rise to a mental image (Tyler et al., 2002b). Words with high imageability such as *bath* have richer semantic features than low imageability words (e.g., *hate*; Jones, 1985; N. Martin & Saffran, 1992; Plaut & Shallice, 1991; Yap et al., 2015) and is often associated with concreteness. Thus, a recall advantage for high imageability/concrete words in vSTM would provide further evidence for the involvement of LTM in vSTM. This advantage has been observed for concrete words over abstract words (Caza & Belleville, 1999; L. M. Miller & Roodenrys, 2009; Walker & Hulme, 1999), and for high imageability words compared to low imageability words in vSTM tasks (Acheson et al., 2010; Bourassa & Besner, 1994; Campoy et al., 2015; Kowialiewski & Majerus, 2018; Savill et al., 2019).

Originally, Hulme et al. (1995) considered that the contribution of LTM in vSTM could only arise from phonological representations. However, in a later study, Walker and Hulme (1999) found that the recall advantage for concrete words – which was observed regardless of the type of recall (verbal, written, or backwards) - did not arise from phonological variables such as speech rate or word length. It was thus assumed that concrete words benefit from richer long-term representations than abstract words, and that this richness favours their recall. In a similar vein, Romani et al. (2008) conducted research to analyse the role of phonological versus semantic representations in verbal short-term memory. They studied the concreteness effect across a variety of tasks - such as free recall, serial recall, order reconstruction, and matching span - both with and without the element of articulatory suppression. Concreteness effects were observed under all conditions, with stronger positive effects in serial recall under articulatory suppression, suggesting that the effect is more substantial when support from phonological representations is weakened, and when an open set of stimuli is used. Taken together, findings of the described studies indicate a reliable contribution of imageability/concreteness on vSTM.

Another effective approach to distinguish between phonological and semantic contributions to vSTM is to provide training on nonwords with or without semantics. If semantics contribute to vSTM beyond phonology, then nonwords that have been taught with an additional semantic layer, along with phonology, should exhibit better recall compared to nonwords that are only trained phonologically. This method was employed by Benetello et al. (2015) who trained unknown words with phonology (i.e., participants learn the phonological form of the word alone) and unknown words with phonology and semantics (i.e., participants learn the phonological form of the word and its meaning). They found no recall advantage for words trained with meaning compared to phonologically familiar words. This led them to conclude that phonological representations play a pivotal role in vSTM, while semantics does not make a substantial contribution to it (for similar conclusions, see Papagno et al., 2013). However, Benetello et al. (2015) used a closed set of stimuli (i.e., items were repeated in the ISR task) and tested each list condition in separated immediate serial recall tasks, which would constrain semantic effects in vSTM. Indeed, in ISR tasks, repeating items tends to excessively activate lexical-semantic representations, which can amplify the retention of the overall order of items and diminishes the influence of lexical-semantic factors on the identity of individual items (Romani et al., 2008; Roodenrys et al., 2000). Therefore, Savill et al. (2017a) used an open set of stimuli of nonwords that were either semantically trained (nonwords associated with an image of an unfamiliar object and its written description), or phonologically familiarised only (nonwords trained without meaning and paired with blurred images only). This approach could have led to the semantically trained items having more meaning than in previous studies where nonwords were only associated with images (Benetello et al., 2015; Savill et al., 2015). Savill et al. (2017) found a recall advantage for semantically trained nonwords over phonologically familiarised items, suggesting that newly acquired semantic representations do contribute to vSTM, irrespectively of phonological-lexical familiarity.

Given the inconsistency in results from previous studies, further evidence would be useful to substantiate the role of lexical-semantic representations beyond just phonological knowledge in vSTM. The methodology used by Savill et al. (2017), which successfully distinguished these types of linguistic representations, offers an excellent model for further investigation. Consequently, this approach will be embraced in both Chapter 2 and Chapter 3 of this thesis. Here, the purpose will be to examine the contributions of both phonological and semantic representations to vSTM in more detail. By doing so, it will perhaps offer a resolution to the current contradictions in the literature.

Summary

The traditional view that STM is distinct from LTM has been challenged by studies suggesting that linguistic knowledge plays a crucial role in STM. While phonological coding is clearly important in vSTM, lexical-semantic knowledge has been found to contribute to STM performance. The contribution of linguistic knowledge to vSTM beyond phonological representations has been demonstrated by the effects of lexicality and frequency, but the contribution of semantic representations to vSTM remains a debated topic. Studies suggest that semantic information stored in long-term memory can enhance function while it may not be necessary for vSTM. Studies have also shown that the degree of semantic similarity between words can affect recall performance. In summary, evidence suggests that both lexical and semantic knowledge contribute to vSTM, but the extent of their contributions may vary depending on the task and the type of linguistic knowledge involved.

The observed contribution of semantic knowledge to vSTM led to the design of STM models that take these data into account or to modify the classical models of STM. I will briefly describe the theoretical conceptions that thus attempt to integrate the role of semantic knowledge in vSTM tasks.

1.5 The nature of the interaction between verbal short-term memory and linguistic knowledge

In the literature, there are two main approaches that are derived from models developed or modified to account for the intervention of long-term linguistic representations in verbal short-term memory (Schwering & MacDonald, 2020). Multi-component models view long-term memory and short-term memory as two distinct systems but interacting (Baddeley, 2000; Hulme et al., 1991; R. C. Martin et al., 1999; Saint-Aubin & Poirier, 1999b; Schweickert, 1993b; Walker & Hulme, 1999), whereas language-based models consider STM as an active part of long-term memory (Cowan, 1999; Majerus, 2013; N. Martin & Saffran, 1997; Patterson et al., 1994).

Multi-component models: separated short-term and long-term stores

According to multi-component models of short-term memory, a system based solely on the activation of representations in long-term memory would not be able to process and learn new information, hence the need for a separated STM store. The first model to be described in this section is Baddeley's (2000) working memory model, which considers the role of long-term memory by introducing a specific component, the episodic buffer, to the initial working memory model (Baddeley & Hitch, 1974). Following this, redintegration models will be explained, they posit a late-stage reconstructive contribution of long-term stored representations (Hulme et al., 1991; Nairne, 1990; Schweickert, 1993b; Walker & Hulme, 1999). Finally, R. C. Martin et al.'s (1999) model considers a close relation between the language system and STM buffers.

Updated working memory model: Baddeley (2000)

Baddeley modified his initial model of working memory (Baddeley & Hitch, 1974b, see **Figure 1.3(a)**) to incorporate the intervention of long-term memory in verbal working memory. The first revision stemmed from the observed correlation between nonword recall and vocabulary acquisition in children, reflecting the contribution of the phonological loop in long-term learning (Baddeley et al., 1998). A long-term phonological store, connected to the phonological loop by virtue of bidirectional connections was added to the initial model (see **Figure 1.3 (b)**).

Nonetheless, this structure does not account for the contribution of semantic knowledge to verbal working memory. Thus, the episodic buffer was later added to the initial model to consider the intervention of semantic knowledge (Baddeley, 2000, see **Figure 1.3 (c)**). The purpose of this buffer was to link the phonological loop and the visuospatial sketchpad to long-term memory, which makes it possible to account for effects that cannot be interpreted by the original model, such as the advantage of sentences in immediate recall (Baddeley & Logie, 1999). The episodic buffer is a temporary storage system that integrates a limited amount of information from various sources. It connects the information of the subsystems into a coherent and complex unitary representation such as a scene or an episode, through a multidimensional code. The integration and maintenance of information in the episodic buffer depends on the central executive, which can influence its content by focusing on a given source of information.

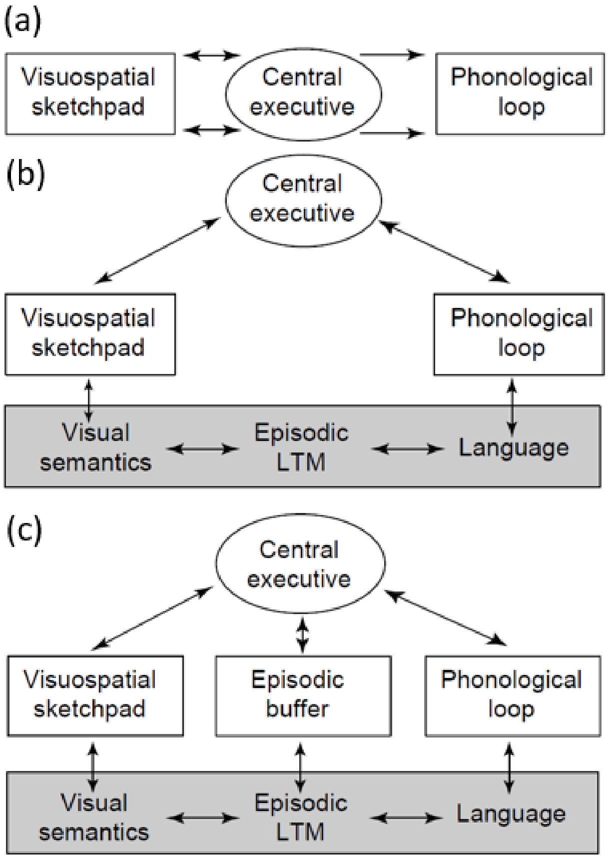

Figure 1.3. *(a) The initial working memory model from (Baddeley & Hitch, 1974). (b) First revision of the working memory model (Baddeley et al., 1998). (c) The current multi-component working memory model (Baddeley, 2000). Figures taken from Baddeley (2000).*

This new component can account for vSTM performance under articulatory suppression, which prevents the intervention of the phonological loop and indicates the intervention of long-term memory (Baddeley et al., 1984). The episodic buffer is capable of accounting for chunking effects as well. This refers to the mechanism of arranging distinct bits of data into larger, coherent units, or "chunks", facilitating a more proficient storage and retrieval of information. As an example, memory span for a meaningful sentence can extend to approximately 16 words (as indicated by Baddeley et al., 1987), in contrast to a span of only five to six words when the words are unrelated. The observed difference between the span of words and the span of sentences suggests that the additional words recalled in the sentence span come from LTM, and that participants are grouping words into larger units. Finally, it accounts for normal span of some amnesic patients in immediate prose recall, although their long-term episodic memory is deficient and the phonological loop is largely exceeded in this task (Baddeley & Wilson, 2002). This further supports the idea that chunking relies on LTM, which is enabled by the episodic buffer.

Redintegration models

The most commonly raised explanation for linguistic effects on vSTM is based on Baddeley's (1974) working memory model and is called redintegration (Hulme et al., 1991; Schweickert, 1993b; Schweickert et al., 1999). Redintegration models do not challenge Baddeley's model and the impact of the articulatory loop on memory span, but they posit the role of another mechanism: redintegration accounts postulate the role of a reconstructive process which involves long-term memory at the stage of recall to fill in for any possible degradation of information maintained in memory by the articulatory loop. According to this hypothesis, if the trace of an item is not degraded, it will be recalled directly from STM storage. However, if a temporary trace is partially degraded, the residual phonological information will be compared with long-term stored representations to identify likely candidate representations to reinstate the trace at the point of recall. For example, the degraded phonological trace of the word *chocolate* may be *choco_*, and its reconstruction may take place through the access of its lexical representation.

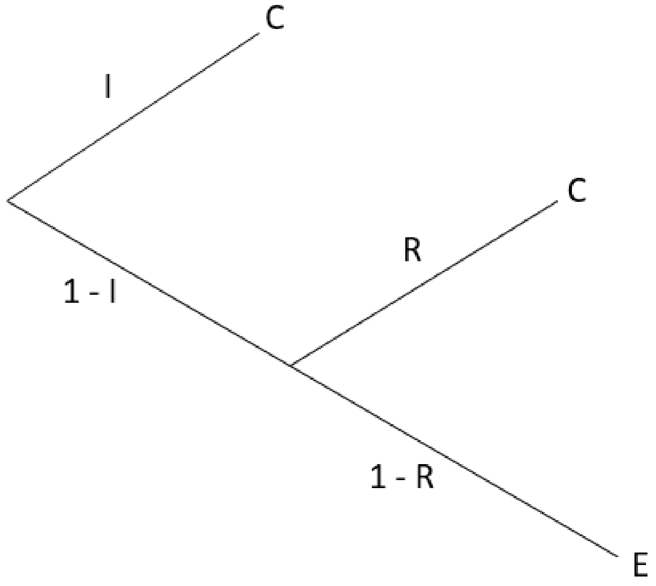

Figure 1.4. The processing tree model, taken from Schweickert (1993). The trace is recalled correctly (C) if it is intact (I) or is successfully reconstructed (R), otherwise an error is produced (E) if this process was unsuccessful. 1-I corresponds to the probability that the trace will not be correct at recall, and 1-R represents the likelihood of incorrectly reconstruct the trace.

Some linguistic effects such as the effect of lexicality or frequency can be accounted for by these models: the more frequent words are, the more readily available their lexical representations will be from long-term memory, so the reconstruction process is more effective for frequent words. There are some differences between redintegration models. For instance, according to Schweickert (1993), lexical long-term memory representations contribute to vSTM only if an initial attempt to recall the item from phonological short-term memory storage has failed. Schweickert's multinomial processing tree model (see **Figure 1.4**) is a statistical framework used to explain cognitive processes in play during short-term recall. The initial effort at recall involves directly fetching the trace from short-term memory, where the likelihood of the trace being undamaged and thus the recall being correct is I. If the trace is degraded, a redintegration mechanism steps in with a probability of $1 - I$, aiming to reconstruct the degraded trace, where the probability of the trace to be correctly reconstructed is R. The probability of recalling an item correctly (PC) is thus represented by the following equation:

$$PC = I + (1 - I)R$$

This redintegration model can explain the recall advantage for words over nonwords in vSTM. The rationale is that nonwords do not have any existing lexical representations, rendering the R parameter (which indicates the likelihood of successful reconstruction) effectively zero. Consequently, the recall of nonwords solely depends on I, indicating an intact phonological memory trace. Nevertheless, it is ambiguous how the deteriorated trace of a word can be differentiated by the system from that of a nonword. Indeed, this model implies that the reconstruction process can be disabled for nonwords, preventing them from incorrectly undergoing the reconstruction process. The model can also explain frequency effects, given that high frequency words are more readily accessible in the mental lexicon, they will benefit from a higher R value than low frequency words. This will increase high frequency words' probability to be correctly recalled.

An issue with Schweickert's (1993) redintegration model is that it struggles to account for semantic effects in vSTM, because reconstruction is supposed to happen at the lexical level. To account for effects of semantic relatedness (i.e., better recall for lists of semantically related words than unrelated words), Poirier and Saint-Aubin (1995) proposed that redintegration can occur at the semantic level. They suggested that knowledge about the type of semantic category can be viewed as merging with degraded phonological traces, thereby offering a more efficient retrieval prompt and boosting the likelihood of successful trace reconstruction. For example, in the list 'pear, plum, fig', the degraded trace '_ig' is more likely to be recalled as 'fig' than 'pig', since the semantic category fruit would have constrained the selection of the correct candidate.

In order to explain concreteness effects in vSTM, Walker and Hulme (1999) extended the redintegration model. They suggested that there could be two parallel processes in operation, with one involved in comparing phonological traces with LTM phonological representations, and the other in matching semantic traces with LTM semantic representations. This resembles the proposition from R. C. Martin et al. (1999) which is described next.

Close but separated stores: R. C. Martin et al. (1999)

The model proposed by R. C. Martin et al. (1999) is inspired by Dell's (1986; Dell & O'Seagdha, 1992; see **Figure 1.5**) interactive activation model: it is based on language processing and posits a strong relationship between language representations and STM.

The authors consider three levels of language representations (phonological, lexical, and semantic) and specific systems dedicated to storage in short-term memory. There are different short-term storage systems, called buffers: the input phonological buffer, the output phonological buffer, and the lexical-semantic buffer. They propose separate phonological and semantic components in short-term memory: a phonological STM, which stores degraded phonological traces, and a semantic STM (or semantic buffer), which stores items' lexical-semantic representations. These buffers have specific, bidirectional connections with stable long-term linguistic representations.

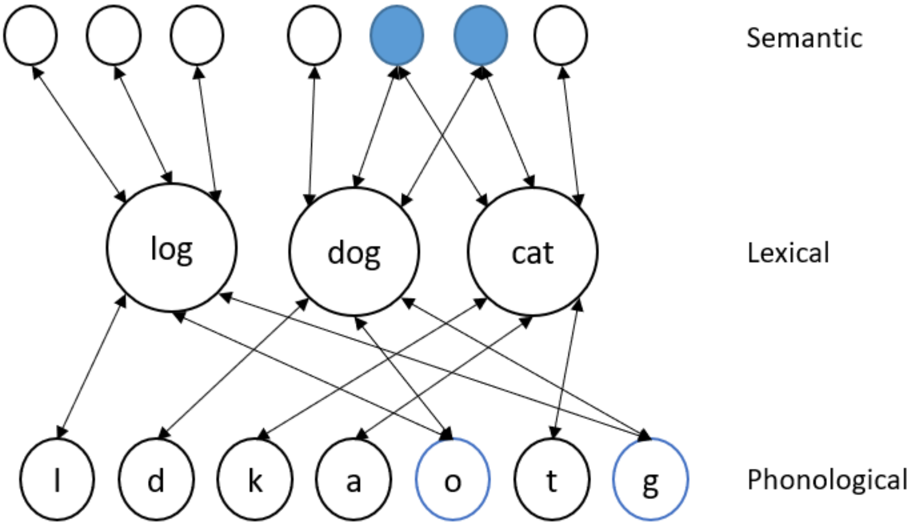

Figure 1.5. *Interactive activation model of language processing (Dell & O'Seagdha, 1992). Shared phonological and semantic activations are shown in blue.*

According to this model, in vSTM tasks, linguistic representations interact with traces temporarily stored in buffers in order to support the degrading traces. More specifically, it is assumed that every level of representation within STM relies on the activation of long-term representations, which are initiated during the encoding process and subsequently sustained throughout the retention phase. Since linguistic representations support degrading traces in vSTM, they intervene similarly to redintegration models. However, unlike these models, the authors assume that this redintegration operates throughout the working memory task, from encoding, and not only at the point of recall. This model therefore considers that a deficit at a given level of representation (phonological or lexical-semantic) will affect the maintenance of information in the corresponding buffer, because these long-term representations will no longer be able to support the buffer's traces. In addition, buffers allow for the storage of the serial order of items, which is essential in serial recall.

The distinction between STM and LTM proposed by R. C. Martin et al. (1999) is supported by neuropsychological studies. For instance, patient AB showed a distinct inability to maintain short-term semantic information. Despite having a maintained span for nonwords, his capacity to remember words was compromised. The authors of the study suggested that AB's semantic buffer was impaired, while his phonological buffer remained intact (Romani & Martin, 1999). Importantly, this patients' access to semantic information was unimpaired, thus, the deficit lies in the short-term retention of semantic information, not in the semantic system per se.

Language-based models: verbal short-term memory as activated linguistic representations

Contrary to multi-component models described above, language-based models of WM/STM do not treat STM and LTM as distinct subsystems. These models were predominantly driven by the assumption that there is a strong correlation between STM and language processing. In these models, vSTM emerges from the language system, and the activation of linguistic representations affects performance. Three models will be described: N. Martin and Saffran's (1997) interactive activation model, the semantic binding hypothesis by Patterson et al. (1994), and the integrative framework by Majerus (2013).

Interactive activation model: N. Martin and Saffran (1997)

Similar to R. C. Martin et al. (1999), the interactive activation model is based on Dell's model (1986; Dell et al., 1997, see **Figure 1.5**). However, N. Martin and Saffran (1997) consider that short-term memory is an emergent property of the temporary activation of linguistic representations (phonological, lexical, and semantic). This model involves a three-level architecture with phonological, lexical, and semantic nodes which are temporarily activated through bidirectional connection weights. In language repetition, activation of phonological representations spreads through the lexical and semantic nodes, and then goes back down to the phonological node. These activations occur in cycles until a response is produced. Therefore, lexical and semantic representations contribute to vSTM by keeping the phonological nodes activated. Two processes are involved in activation and maintenance of linguistic representations: connection weights between the different nodes, which determine the amount of activation that spreads from one node to another; and the degradation speed (decay rate) of activations, which prevents the system to become saturated.

In the case of a weakening of the connections between different nodes, activation propagates less efficiently. Thus, the phonological representations will be correctly activated, and their activation will be maintained, but the lexical representations, and especially the semantic representations which are furthest away, will be less and less activated. This can result in phonemic paraphasias in word repetition because phonological representations, due to the absence of feedback from lexical representations, will not be correctly selected. In vSTM tasks, this will result in a decreased lexicality effect, an absence of the primacy effect (since the first items depend on lexical and semantic representations), and a reduced recency effect due to the absence of feedback from lexical and semantic representations on the selection and maintenance of the activation of phonological representations. The recall of nonwords will be preserved. On the other hand, an increased decay rate will result in the opposite profile. Since phonological representations are activated first, they will be more affected by this increase in the speed of decay. The response will then depend only on the selection and maintenance of the activation of lexical and semantic representations. Thus, in STM tasks, nonwords recall will be impaired, and the recency effect will be absent since it depends on phonological representations. The primacy effect will be preserved.

The interactive activation model is supported by neuropsychological data (N. Martin et al., 1994; N. Martin & Saffran, 1992), and in particular by the syndrome of deep dysphasia, a subtype of aphasia characterised by a reduced vSTM span, difficulties in nonwords repetition, and the production of semantic errors. In N. Martin and Saffran (1992), patient NC showed an inability to repeat nonwords, semantic paraphasias, and a memory span of one item. This pattern of results can be accounted for by a rapid decay rate of the temporary activation of phonological, lexical, and semantic representations. Nonword repetition is altered because the activation of phonological nodes cannot be supported by lexical and semantic representations and the rapid decay of phonological activations, occurring before the phonological trace can be translated to an output, results in the inability to repeat nonwords. This account was later supported by interactive activation computational simulations (N. Martin et al., 1994), suggesting that vSTM is a property of the language system.

In essence, the interactive activation model considers the role of various lexical-semantic representations in short-term recall, STM is sustained by the reciprocal activations amongst phonological, lexical, and semantic representations within the language system.

Semantic binding hypothesis: Patterson et al. (1994)

Patterson et al. (1994) proposed a hypothesis that aligns with interactive activation models, forwarding what they termed the 'semantic binding hypothesis' (Knott et al., 1997). This hypothesis proposes that vSTM emerges from the interaction between linguistic representations. However, contrary to N. Martin and Saffran (1997), their hypothesis is based on a different theoretical premise: parallel distributed processing models (e.g., Seidenberg & McClelland, 1989). These models are founded on the idea of neural networks, where information processing takes place concurrently across several interconnected nodes at the phonological and semantic levels. A noteworthy point about the semantic binding hypothesis, and where it deviates from interactive activation models, is its absence of a proposed distinct lexical level of representation.

According to the semantic binding hypothesis (Patterson et al., 1994), vSTM is an emergent property of the linguistic system (similar to N. Martin & Saffran, 1997), which provides a source of constraint in two ways. The first one occurs through the ‘phonological level’, which is activated each time a word is encountered and thus retains the correct phonological configuration of the words. The second source of constraint stems from the ‘semantic level’, since the meaning of a word is generally accessed whenever a word is produced or heard. This enables the semantic system to enhance the phonological activation patterns associated with a specific meaning. Thus, semantic information improves the strength of associated phonological representations, and interactions between phonological and semantic levels bind constituents of a word together, a process that occurs at the encoding stage in vSTM tasks and allows for constituents of a word to be correctly recalled.

The semantic binding hypothesis was inspired by errors produced by neuropsychological patients (Hoffman et al., 2009; Jefferies, Jones, et al., 2004; Knott et al., 1997; Patterson et al., 1994). Typically, patients with semantic dementia produce phonological errors (i.e., phoneme migrations, see section 1.4) for words they poorly understand in immediate serial recall. This can be explained by the lack of semantic support which leaves phonemes vulnerable to breaking apart from one another. Similar results have been found in healthy participants in vSTM tasks using nonword lists: nonwords do not enjoy semantic representations, therefore, nonwords phonemes are more likely to migrate within the list than meaningful words (Jefferies, Frankish, & Lambon Ralph, 2006b; Savill et al., 2017). This suggests that lexical-semantic representations impact the coherence of the phonological trace in vSTM.

The integrative framework: Majerus (2013, 2019)

The integrative framework of short-term memory proposed by Majerus (2013) aimed at filling some gaps left from earlier models previously described. It is integrative since it considers that item memory emerges from the linguistic system (similar to other language-based models), as well as from separated networks for order memory and attentional systems. It also relates these components of short-term memory to underlying neural substrates (see **Figure 1.6**). More precisely, the dorsal pathway[6] is involved in the maintenance of a word's constituent phonemes in order (i.e., item memory) and the ventral pathway[7] processes semantics. This resonates with the interactive activation model (N. Martin & Saffran, 1997) and the semantic binding hypothesis (Patterson et al., 1994) in that short-term memory is considered to arise from an activated portion of linguistic long-term memory.

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[6] The dorsal pathway connects posterior regions of the temporal lobe with the posterior inferior frontal cortex.

[7] The ventral pathway involves connections between the posterior superior temporal gyrus (pSTG) and middle temporal gyrus (MTG), extending anteriorly to the inferior frontal gyrus.

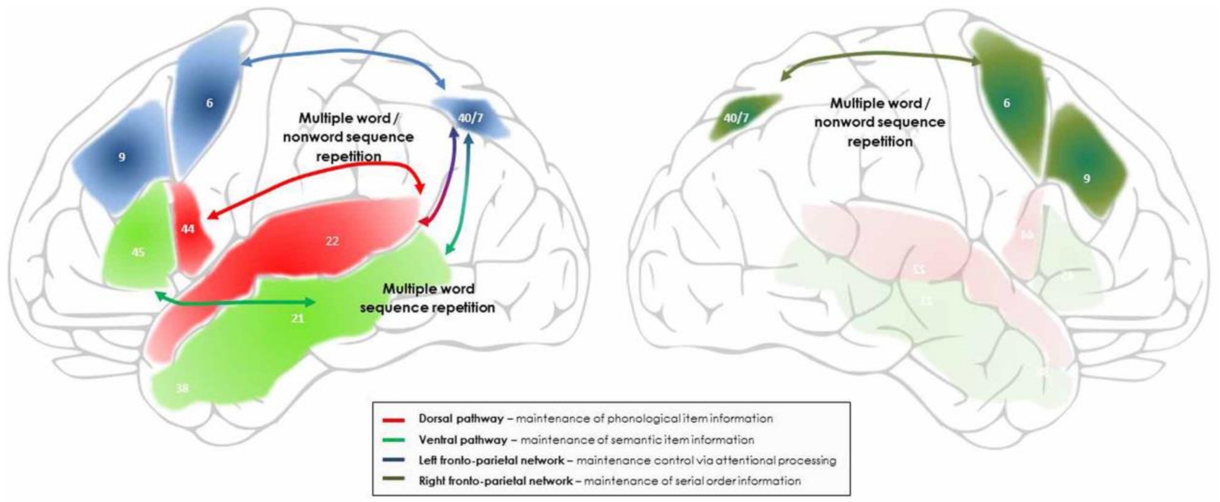

Figure 1.6. *The integrative framework from Majerus (2013).*

Most language-based models do not include a mechanism involved in serial order maintenance, which is typically not considered to be impacted by long-term linguistic representations (Allen & Hulme, 2006; Campoy et al., 2015; Gathercole et al., 2001a; Hulme et al., 1997; Poirier & Saint-Aubin, 1995; Romani et al., 2008; Tse & Altarriba, 2007). Within the integrative framework, serial order information is maintained via the right fronto-parietal network - associating the right intraparietal sulcus to the right superior and middle prefrontal cortex - which intervenes simultaneously with the language pathways and allows for the maintenance of the order in which words appear in a list, and maintenance of phonemes order for unfamiliar words or nonwords. Similar to Cowan (1999), attentional processing – situated in the fronto-parietal network – allows for attentional focalisation for the maintenance of representations temporarily activated in the language pathways, and control towards the most relevant stimulus. This distinction between item and order information has been supported by neuroimaging and neuropsychological studies (Guidali et al., 2019; Kalm & Norris, 2014; Majerus, 2008; Papagno et al., 2017), but also contradicted by "rich emergent" models that envisage verbal short-term memory as fully ingrained in the language system (Schwering & MacDonald, 2020).

Rich emergent models of vSTM propose a more integrated approach to understanding memory and language processes. Instead of segregating vSTM and language into separate systems, these models emphasise the interconnectedness of the two and their role in cognitive processing (Acheson & MacDonald, 2009b; Schwering &

MacDonald, 2020). According to this perspective, performance on vSTM tasks is mainly driven by linguistic knowledge, including phonological, lexical, semantic, and syntactic information. Therefore, it suggests that there is no need for separate item and order storage mechanisms. However, neuroimaging findings suggest that separate neural mechanisms handle item and order information (Majerus, 2009).

Summary

The analysis of both multicomponent and language-based models indicates a universal acknowledgment of the influence of long-term stored linguistic knowledge on vSTM. However, the nature of the relation between short-term and long-term memory remains a topic of contention. On the one hand, multicomponent models (Baddeley, 2000; Hulme et al., 1991; Schweickert et al., 1999) consider vSTM and long-term memory as two separated systems, and the redintegration account in particular envisages the contribution of linguistic knowledge as a late-stage reconstructive process, suggesting that psycholinguistic effects on vSTM arise at the point of recall, through the reconstruction of the degraded phonological trace.

On the other hand, language-based models posit that vSTM emerges directly from long-term memory, without the need for a separated store. Interactive activation models and their derivatives assume that the impact of long-term knowledge on vSTM performance (i.e., lexicality and semantic effects) occurs from the encoding stage, in a relatively automatic way, since vSTM stems from the activation of phonological, lexical, and semantic representations. Therefore, one of the aims of the present thesis will be to analyse item-level and phoneme-level immediate serial recall performance with a range of linguistic representations, in order to examine predictions from the semantic binding hypothesis (Patterson et al., 1994).

A pivotal theme underpinning questions in this thesis is the potential interplay and mutual reinforcement between phonological and semantic representations in vSTM, a topic discussed in section 1.3. As demonstrated by Savill et al. (2019), this interaction seems to become particularly important in conditions where phonological representations are relatively weak, and if this is the case, ought to have implications for developmental dyslexia. Dyslexia exemplifies a condition where phonological representations, crucial to vSTM, are often less robustly or less effectively accessed (e.g., Ramus & Szenkovits, 2008; Savill & Thierry, 2012). Examining dyslexia offers an opportunity to deepen our understanding of the phonological-semantic dynamic in vSTM. Rather than viewing dyslexia merely as a condition of phonological weaknesses, it is important to consider how semantic compensation may operate in these instances, thus highlighting the rationale behind exploring this relationship further.

The subsequent section thus provides a brief overview of developmental dyslexia. It expands on the empirical evidence illustrating the compensatory role of semantic representations found in reading and broader context for examining the phonological-semantic relationship in vSTM in dyslexia.

1.6 Developmental dyslexia

Definition(s) and theoretical accounts

A clear definition of developmental dyslexia, or specific reading disability (dyslexia hereafter), is crucial for conducting precise theoretical research and for allowing reproducibility of this work. Over decades of research the term 'developmental dyslexia' has been used to describe a range of learning difficulties. This phrase encompasses a variety of definitions, emphasising the impact of the condition on language and literacy skills. In the United Kingdom, the definition of dyslexia adopted by the British Dyslexia Association was formulated by Rose (2009):

> Dyslexia is a learning difficulty that primarily affects the skills involved in accurate and fluent word reading and spelling. Characteristic features of dyslexia are difficulties in phonological awareness, verbal memory and verbal processing speed. Dyslexia occurs across the range of intellectual abilities. It is best thought of as a continuum, not a distinct category, and there are no clear cut-off points. Co-occurring difficulties may be seen in aspects of language, motor co-ordination, mental calculation, concentration and personal organisation, but these are not, by themselves, markers of dyslexia. A good indication of the severity and persistence of dyslexic difficulties can be gained by examining how the individual responds or has responded to well-founded intervention. (p. 191)

Given that a child's usual progression in reading entails connecting letters with previously acquired language sounds (i.e., the conversion from orthography to phonology), it is widely accepted that poor phonological abilities can hinder the process of learning to read (Carroll & Snowling, 2004; Shankweiler et al., 1979; Snowling, 2000; Snowling et al., 2020; Snowling & Hulme, 1994). There is thus a consensus amongst researchers that difficulties in delineating or accessing phonological representations while reading underpins a significant number of dyslexia cases. Most definitions of dyslexia agree on the notion of specific disorder and support the idea that reading difficulties cannot be explained by more general factors (Ramus, 2014). Another criterion refers to the persistence of symptoms. According to some authors, this criterion allows to distinguish dyslexia from poor reading whereby dyslexia is considered to result from a neurodevelopmental disorder with genetic origins (Carrion-Castillo et al., 2013; Démonet et al., 2004; Fisher & DeFries, 2002), while poor reading would be more closely linked to environmental factors (Vellutino et al., 1996).

Co-occurring disorders with dyslexia are a common phenomenon. These can be related to language such as 'specific language impairment' (or developmental language disorder, see Bishop, 2017), manifesting as difficulties with oral language, which has been found to be co-occurring in half of the children with dyslexia (McArthur et al., 2000). Comorbidities can also be psychiatric. For instance, Attention Deficit Hyperactivity Disorder (ADHD) is frequently observed in individuals with dyslexia (Carroll et al., 2005; Germanò et al., 2010; McGee et al., 2002; Trzesniewski et al., 2006; Willcutt et al., 2005). Dyscalculia, a disorder that hampers the comprehension of arithmetic, is also reported in some dyslexic individuals, causing additional difficulties in learning and performing mathematical tasks (Landerl et al., 2009; Träff et al., 2017; Von Aster & Shalev, 2007). These comorbid deficits may exacerbate the learning challenges faced by individuals with dyslexia, necessitating the development of multidimensional intervention strategies that address these intertwined issues.

Heterogeneity of dyslexia

The heterogeneity of cognitive and behavioural profiles observed amongst the dyslexic population motivated the identification of three major sub-categories of dyslexia. Reading words relies on various cognitive functions, which are outlined in two major models of word reading, and these have been variously applied to explain the different profile of reading abilities, including developmental and acquired dyslexias: the triangle/connectionist models (Seidenberg & McClelland, 1989), and the dual-route model of reading aloud and visual word recognition (Coltheart et al., 2001). The triangle model of reading (see section 1.3), is a connectionist approach to understanding word recognition and reading aloud. The model proposes two pathways through which a written word can be transformed into speech: the semantic pathway which is primarily used for irregular or exception words whose pronunciations cannot be easily determined from their spellings, such as "yacht", and the phonological route which mainly is used for regular words and nonwords whose pronunciation can be determined from their spellings. The semantic pathway connects phonological, orthographical and semantic nodes, whereas the phonological pathway connects between phonological and orthographical representations.

According to the triangle model, phonological dyslexia – a neuropsychological profile characterised by a difficulty to read nonwords (but also used to describe developmental profiles)- could be a result of impairment to the phonological route (Patterson & Lambon Ralph, 1999). As this pathway is used for sounding out words, especially nonwords, its damage would lead to difficulties in processing nonwords, while reading regular and irregular words (processed via the semantic route) would be relatively unaffected. Another type of dyslexia is surface dyslexia, where individuals struggle to read irregular words but can read regular words and nonwords relatively well. This form of dyslexia could be a result of damage to the semantic pathway (Woollams et al., 2007). Since the semantic pathway is mainly used for irregular words, any disruption to this route would lead to difficulties in processing these words while the ability to read regular words and nonwords (processed via the phonological route) would be preserved. Finally, mixed dyslexia could occur as a result of impairment to both the phonological and semantic routes, leading to difficulties in reading both regular and irregular words as well as nonwords.

The dual-route model posits that reading is achieved via separate lexical and sublexical procedures, referring to the direct mapping between words and their meaning with access of the word as a whole (used to read regular words and exception words), and grapheme-phoneme correspondence (used to read nonwords and unfamiliar) respectively (Coltheart et al., 2001). According to the dual-route model, dyslexia could be the result of difficulties in either the lexical or the sublexical route: Phonological dyslexia is characterised by difficulty using the sublexical route, necessary for reading new words or nonwords. The second form of dyslexia is called 'surface dyslexia' and is characterised by the systematic use of the grapheme-phoneme pathway due to difficulty in relying on the lexical route. The third type of dyslexia corresponds to mixed dyslexia with difficulties using the lexical and sublexical pathways. In essence, while the dual-route model focuses on separate pathways for different word types, the triangle model places more emphasis on the interaction and balance between phonological and semantic processing in reading, allowing for differences in learning and potential compensatory mechanisms to occur.

The relevance of these subtypes defined based on reading profiles is not unanimous in the literature (e.g., Zoubrinetzky & Valdois, 2014). Although these types of dyslexia have been identified, the precise origin of the condition continues to be a topic of discussion. Thus, various theoretical frameworks have been proposed as potential explanations of dyslexia. The phonological hypothesis maintains a dominant position in academic discourse and holds substantial relevance for the rationale of this thesis. Therefore, I will detail this theory first, followed by a succinct summary of other proposed theories.

Phonological theories

Phonological hypotheses of dyslexia have been the most influential in recent decades and have been studied extensively (Griffiths & Snowling, 2002; Ramus et al., 2013; Snowling, 2000; Swan & Goswami, 1997; Vellutino et al., 2004a). It posits that weak phonological processing would disrupt the learning of the grapheme-phoneme correspondence, leading to difficulties in reading acquisition (Ramus, 2003).

The phonological representations hypothesis specifically proposes that dyslexia is underpinned by a dysfunction at the level of phonological representations, with degraded, less precise, less structured, underspecified, and less stable mental representations of phonemes (Snowling, 2000). This results in poor manipulation, segmentation, access, storage and retrieval of phonemic information, as evidenced by dyslexics' poorer performance compared to control participants at a range of phonological tasks. These tasks include nonword repetition (Elbro et al., 1998; Snowling, 1981), verbal short-term memory (Hulme, 1981), phonological awareness[8] (Morris et al., 1998), rapid automized naming or RAN (in which participants name a series of items presented on a sheet as quickly as possible, Denckla & Rudel, 1976), and verbal paired associate learning (Wimmer et al., 1998). Deficits in RAN tasks are usually interpreted in the context of impaired phonological representations, with difficulties to retrieve phonological representations (Murphy et al., 1988). However, problems at the level of phonological representations are not necessarily implicated by difficulties in performing such tasks. Indeed, Ramus and Szenkovits (2008) suggest intact phonological representations, but, instead, a deficit in accessing these representations.

Ramus and Szenkovits (2008) suggest that the phonological deficits reported in dyslexics does not stem from weak phonological representations, but instead arises from phonological access difficulties (Boets et al., 2013; Mundy & Carroll, 2012). That is, when assessing phonological representations of adults with dyslexia via specifically designed tasks (such as discrimination and repetition of Korean compared to French (native) speech sounds (Soroli et al., 2010), phonological similarity, voicing assimilation in reading aloud, and repetition priming), Ramus and Szenkovits (2008) found no difference between dyslexic and control groups' performance, even though dyslexic participants had a phonological deficit as shown by their performance with traditional phonological tests (i.e., rapid naming, spoonerisms, nonword repetition). In order to complete these traditional tasks, participants needed to access phonological representations to manipulate them in working memory, and this seemed to be the source of the phonological deficit observed in dyslexia. As Ramus and Szenkovits (2008) point out, "the auditory and visual representations of people with dyslexia are intact, but that they have difficulties accessing them under certain conditions involving storage in short-term

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[8] Phonological awareness is the ability to perceive and manipulate the sounds of spoken words, that is, phonemes. It covers a wide range of tasks ranging from rhyme judgement to more complex tasks such as phonemic deletion or substitution. This ability seems to be a good predictor of reading development (see Castles & Coltheart, 2004).

memory, speeded or repeated retrievals, extraction from noise, and other task difficulty factors” (p. 139). They suggest difference in group performance is modulated by task demands, particularly when working memory load is increased. This hypothesis has been supported by Boets et al (2013) who, using neuroimaging, showed no difference in activation between individuals with and without dyslexia in areas that store phonological representations within the superior temporal gyrus. On the other hand, the functional connectivity between these areas and Broca's area, known for its role in accessing phonological representations enabling language production, was different between the two groups. This seems to reflect intact phonological representations and difficulties in accessing them in individuals with dyslexia. In a similar vein, Savill and Thierry (2012) suggested that dyslexic individuals might have difficulties retrieving phonological information instead of recognising it, which might arise from attentional challenges. However, these studies are mainly based on dyslexic adults, who may have reached a 'normal' level of phonological representations, while the deficit could be on both levels in children: they could suffer from both slower development of phonological representations and disrupted access to these representations (Ramus & Szenkovits, 2008; Savill & Thierry, 2012).

Other perspectives highlight the importance of attention in the occurrence of reading difficulties (Bosse et al., 2007; Facoetti et al., 2006; Hari & Renvall, 2001; Roach & Hogben, 2007; Valdois et al., 2004; Vidyasagar & Pammer, 2010). For instance, the visual attention span deficit hypothesis argues that individuals with dyslexia have a reduced capacity to simultaneously process multiple visual elements. This difficulty would affect their ability to recognise strings of letters or words at a glance, leading to slow, effortful reading. In addition, the attentional shifting deficit theory posits that dyslexics suffer from sluggish disengagement of attention and insufficient engagement, evident across both auditory and visual domains (Facoetti et al., 2006; Hari & Renvall, 2001). These deficits interfere with the sequential attention shifts needed in text scanning and sublexical reading, ultimately impairing decoding and the mapping of spelling to sound.

The Double Deficit Hypothesis by Wolf and Bowers (1999) suggests that some children with reading disabilities show individual deficits in phonological awareness or rapid automated naming (RAN), or both. This approach considers developmental dyslexia as a result of independent cognitive deficits, with RAN potentially indicating a separate orthography-phonology timing mechanism. The theory is supported by stronger correlations between RAN skills and exception word reading than between phoneme awareness and exception word reading (Manis et al., 2000). Additionally, Boets et al. (2010) found that phonological abilities and RAN capacities were the best predictors of reading accuracy and speed, respectively. However, other research posits that RAN could represent the efficiency of phonological representation activation, thus conflicting with the double deficit theory (Vaessen et al., 2009).

Other theoretical perspectives

Despite attempts to establish a unified framework of dyslexia, cognitive impairments associated with this learning disorder are too varied to be explained by any single theory. Besides the phonological hypothesis, the most prominent approaches have focused on aspects such as auditory and visual perception. The auditory deficit theory posits that individuals with dyslexia have difficulties processing brief, rapidly varying auditory information, specifically phonemes (Tallal et al., 1993; Temple et al., 2000). According to this theory, this temporal processing deficit interferes with the ability to differentiate and sequence sounds, and to establish phonological representations, which is critical for understanding and reproducing language, thus leading to difficulties in acquiring reading skills. On the other hand, the visual magnocellular deficit theory suggests that individuals with dyslexia have a specific dysfunction of the magnocellular pathway in the visual system which allows the processing of low spatial frequencies, and is involved in the control of eye movements (Lovegrove et al., 1980; Stein, 2001; Stein & Walsh, 1997). This could potentially result in issues such as poor eye movement control, slow reading speed, and difficulties with tasks that require the processing of rapidly changing visual information, all of which are common symptoms in dyslexia.

The Serial Order in Verbal Short-Term Memory (SOLID) hypothesis, proposed by Szmalec et al. (2011), suggests that dyslexia could result from difficulties with the serial ordering of information in verbal short-term memory. This hypothesis proposes that this deficit might disrupt the formation of stable phonological representations in long-term memory, thereby influencing language and reading development. This perspective shifts the focus from traditional phonological deficits in dyslexia to problems with sequential or temporal processing. Finally, motor-learning theories with the automaticity/cerebellar deficit hypothesis suggest that dyslexia may be the result of a deficit in the cerebellum, a part of the brain that is essential for automating learned tasks (Nicolson & Fawcett, 1990).

While some of these theories move further away from a phonological explanation of dyslexia (e.g., the magnocellular deficit theory), there is little disagreement that phonological processing seems to be relatively weak in dyslexic individuals (Lyon et al., 2003). It is on this premise that the work presented in this thesis will be based on the phonological deficit hypothesis, with the recruitment of participants with phonological dyslexia.

Short-term memory deficits in dyslexia

Dyslexia not only manifests as substantial and ongoing challenges in written language, but also brings with it – compatible with a context of ongoing phonological processing difficulties – associated issues such as working memory and short-term memory impairments (Snowling, 2000). Working memory is involved in many academic areas such as mathematics and reading, and is also important for learning new words. Thus, STM deficits could exacerbate learning difficulties in these domains (Attout et al., 2014; Gathercole et al., 2004, 2006; Gathercole & Baddeley, 1993).

Understanding the STM impairments in dyslexia is a challenging task. This is due to the potential interplay between these STM issues and the language difficulties that are integral characteristics of dyslexia. Dyslexia is primarily defined by modifications in phonological representations or the ability to access them (Ramus, 2003; Ramus & Szenkovits, 2008; Snowling, 2000), which could potentially result in difficulties to encode information swiftly and accurately in vSTM tasks.

To understand STM deficits in dyslexia, it is appropriate to differentiate two aspects: the information to be remembered (item information) and the sequence in which the information is presented (serial order). Item information refers to the identity of the items, whereas serial order refers to the sequence in which the items are presented (Majerus et al., 2007, 2015). Research suggests that difficulties in dyslexia may be tied to both aspects, but they might be affected differently (Wokuri et al., 2023). Majerus and

Cowan (2016) conducted a literature review on studies contrasting the item and serial order aspects in STM amongst children with dyslexia or adults with a history of developmental dyslexia. This review showed that phonological impairments characterising dyslexia can lead to difficulties in maintaining item information, particularly phonological item information. On the other hand, maintaining serial order might depend on processes that may be distinct from the language system, and seems to show deficits in dyslexia (Majerus & Poncelet, 2017; Martinez-Perez et al., 2015). The deficit in the serial order is also observed in visual-spatial STM tasks, which undermines the possibility that STM difficulties in individuals with dyslexia are solely the result of underlying phonological disorders (Romani et al., 2015).

Corroborating the above ideas, Martinez-Perez et al. (2013) revealed a verbal STM deficit in dyslexic adults for both item and serial order information with no correlation between these two aspects, suggesting an independence of these two processes in STM. Other researchers report findings in favour of a specificity of serial order memory impairments in dyslexia, notably as a consequence of a STM impairment affecting serial order of both verbal and visual information (Hachmann et al., 2014; Martinez-Perez et al., 2015). Neuroimaging studies provide further evidence for serial order difficulties in verbal and visuo-spatial STM. Martinez-Perez et al. (2015) examined the neural networks associated with item and serial order information in STM using probe recognition tasks of verbal items, visual items, and serial order. Results showed that even if there are deficits for item and serial order STM, they are associated with different neural networks. On the one hand, during visual and verbal serial order STM tasks, dyslexics showed under-activation in the right intraparietal sulcus and the superior frontal sulcus. According to Martinez-Perez et al. (2015), these regions can be considered as being involved in serial order STM (see also Majerus et al., 2006). On the other hand, during STM tests assessing item information, dyslexics showed over-activation of "the left intraparietal cortex, the bilateral cingulate cortex and the right dorsolateral prefrontal cortex" (Majerus & Cowan, 2016, p.5), which are brain regions that seem to be involved in the manipulation of information in working memory and attentional control (Majerus et al., 2016). This suggests that these individuals are exerting more effort or recruiting additional resources to process item information, which could reflect a compensatory mechanism. However, despite this over-activation, individuals still experience difficulties, indicative of a fundamental STM deficit.

Contrastingly, in Wang et al. (2016), university students with a history of dyslexia showed a preservation of STM at both the serial order and item level in immediate serial recall tasks. Perhaps the choice of stimuli used by Wang et al. (2016) may have contributed to the lack of observed group differences. The immediate serial recall (ISR) lists used in the study comprised six written words that were manipulated for phonological and semantic similarity. The use of real words, which inherently carry lexical-semantic information, could potentially provide supportive cues that enhance recall performance for dyslexic individuals, thereby minimising group differences. Their approach contrasts with several other studies that found vSTM deficits in dyslexic individuals when nonword stimuli were used (for example, Martinez-Perez et al., 2012). Nonwords lack lexical-semantic information that can aid in recall, thereby presenting a greater challenge to vSTM. The use of nonword stimuli might be more sensitive to potential group differences in vSTM performance related to dyslexia. This underscores the relevance of what is being held in vSTM and highlights the importance of stimulus selection in studying vSTM deficits in dyslexia.

In summary, it appears that the difficulties of dyslexic children and adults in STM tasks are linked, on the one hand, to an alteration of phonological representations in long-term memory and, on the other hand, to a dysfunction of general attentional mechanisms of working memory. An important element to consider is the heterogeneity of STM deficits in dyslexia. The studies reported above show that overall, dyslexic individuals have difficulties with phonological item STM and serial order STM. However, these results are based on group studies, and not all participants will necessarily present the same deficits. These deficits are important to consider in order to help dyslexic individuals progress in their learning despite their challenges.

Semantic compensation in dyslexia?

According to the triangle model (Seidenberg & McClelland, 1989) and the primary systems hypothesis (Patterson & Lambon Ralph, 1999), individuals with lower reading skills might leverage additional semantic pathway resources to bolster their phonological pathway while performing phonological tasks such as reading. Indeed, poor phonological abilities can disrupt the mapping between orthography and phonology involved in reading (Hulme & Snowling, 1992), which, according to the division of labour principle previously mentioned (see section 1.3), can be supported by semantic knowledge (Strain & Herdman, 1999). This is supported by Siegelman et al.'s (2020) study where children aged eight to eleven, with varying levels of reading ability, completed a word naming task in which phonotactic probability, imageability, and frequency were manipulated. Readers with typical skills showed greater sensitivity to phonological consistency while demonstrating less sensitivity to imageability. In contrast, less skilled readers exhibited a heightened sensitivity to imageability and a diminished sensitivity to phonological consistency. Thus, the level of reading skill could be defined by an increased sensitivity to phonological information, automatic engagement of the phonological pathway, and a decreased sensitivity to semantic information.

Likewise, children with dyslexia seem to use semantic and morphological information to compensate for their phonological difficulties in reading (Betjemann & Keenan, 2008; Elbro et al., 1998; Hennessey et al., 2012; Nation & Snowling, 1998a; A. de P. Nobre et al., 2016; Quémart & Casalis, 2015). For example, with a picture-word priming paradigm, van der Kleij et al. (2019) found stronger effects of semantic priming in primary school children with dyslexia compared to typical readers, suggesting stronger reliance on semantic knowledge in reading. In this study, written words that children read aloud were either preceded with phonological or semantic primes. While children with and without dyslexia showed similar sensitivity to phonological primes, dyslexic children were more sensitive to semantic primes. In addition, authors found a correlation between reading abilities and semantic priming in dyslexic children, suggesting that dyslexic children that developed better reading abilities were also better able to compensate with semantic knowledge. In the same vein, van Rijthoven et al. (2018) reported that in 9-year-old dyslexic children, decoding and word identification performance were predicted by their semantic abilities. Well-developed semantic abilities seem to reinforce weak phonological skills in reading development.

Reading, a context-rich activity, may enable individuals with dyslexia to rely more heavily on semantic understanding to grasp the overall meaning (Nation & Snowling, 1998a). Evidence indicates that these top-down processes can enhance reading comprehension for dyslexics, who tend to depend more on contextual indicators such as semantics and syntax when deciphering words. Conversely, proficient readers typically employ more efficient bottom-up strategies (Bruck, 1988; Nation & Snowling, 1998a; Stanovich et al., 1986). Nation and Snowling (1998) found that dyslexic children utilise semantic context as a compensatory strategy to offset the effects of their decoding challenges during reading. Dyslexic individuals may leverage their pre-existing knowledge, established lexical representations, and predictive skills to counterbalance phonological deficits in reading. Additionally, they may utilise broader contextual cues, which offer a more substantial semantic framework for comprehension.

Phonological impairments found in children with dyslexia seem to persist into adulthood (Callens et al., 2012; Lefly & Pennington, 1991; J. Martin et al., 2010; Swanson & Hsieh, 2009). Bruck (1992) noted that for university students with dyslexia, phonological awareness does not improve with age, and it has been suggested that this phonological deficit may worsen over time (Miller-Shaul, 2005). However, research suggests that, similarly to children with dyslexia, dyslexic adults can compensate for these weaknesses by relying on context, morphological and semantic knowledge (Cavalli, Colé, et al., 2017; Cavalli, Duncan, et al., 2017; Chiarello et al., 2006; J. Martin et al., 2014; Schiff et al., 2019; S. E. Shaywitz et al., 2003). Accordingly, Ben-Dror et al. (1991) found that dyslexic students showed greater effects of sentence context in a word naming task than control participants. In addition, Cavalli et al. (2016) suggested that vocabulary skills - preserved in university students with dyslexia - seem to moderate the relationship between phonological performance and reading comprehension (see also Ransby & Swanson, 2003).

Further evidence of the benefit of semantic or more broadly declarative memory in reading comprehension has been provided by electrophysiological and neuroimaging studies in adults and children (Cantiani et al., 2013; Cavalli, Colé, et al., 2017; Eden et al., 2004; Gebauer et al., 2012; Hedenius et al., 2013; Krafnick et al., 2011; Paz-Alonso et al., 2018; Temple et al., 2003; Ullman & Pullman, 2015). While reduced activation of the reading network in the left hemisphere (including the inferior frontal gyrus, the fusiform gyrus, the ventral occipitotemporal cortex, parietal and ventral regions) has been consistently observed in individuals with dyslexia (Centanni et al., 2019; Chyl et al., 2018; Hoeft et al., 2007; Paulesu et al., 2014; Paz-Alonso et al., 2018; Richards & Berninger, 2008; Richlan, 2012), Paz-Alonso et al. (2018) found stronger functional connectivity between hypoactivated reading nodes in reading aloud, which may reflect compensatory mechanisms (see also Koyama et al., 2013). Moreover, after remediation, the right hemisphere seems to play a compensatory role in reading (Barquero et al., 2014; Temple et al., 2003). These results should however be interpreted with caution due to the variability of the results based on tasks demands (Ramus & Szenkovits, 2008; Waldie et al., 2013).

At the neural level, within the left hemispehere, the phonological pathway of the triangle model is associated with the dorsal pathway which includes the supramarginal gyrus, the dorsal subregion of the inferior frontal gyrus, the superior temporal gyrus, and the supramarginal gyrus (Bitan et al., 2007; Brozdowski & Booth, 2021; Jobard et al., 2003; Mathur et al., 2020; Nixon et al., 2004; Perrone-Bertolotti et al., 2017; Vigneau et al., 2006). The semantic pathway (i.e., ventral pathway) recruits the angular gyrus, the middle temporal gyrus, and ventral regions inferior frontal gyrus (Binder et al., 2009; Mathur et al., 2020; Mechelli et al., 2007). The right hemisphere has been found to be involved in semantic processing, but not phonological processing (Vigneau et al., 2011). Children with dyslexia seem to show difficulties to recruit posterior regions involved in the reading network in the left hemisphere (Paulesu et al., 2001; Pugh et al., 2000; B. A. Shaywitz et al., 2002). Possibly to compensate for the under-activation of left posterior regions, dyslexic individuals seem to recruit frontal and right hemisphere sites to a greater extent than non-dyslexic individuals (Brunswick et al., 1999; Démonet et al., 2004; Hoeft et al., 2007; Pugh et al., 2000; S. E. Shaywitz et al., 1998; Simos et al., 2002; Waldie et al., 2013). Overall, children with dyslexia might employ distinct neural routes for reading compared to their peers without dyslexia, as an adaptive response to under-activations in left posterior regions. This is in line with connectionist models of reading where semantic representations have bidirectional connections with both phonological and orthographic representations (Seidenberg & McClelland, 1989). However, other studies have found under-activation of these regions (Paulesu et al., 1996; Rumsey et al., 1997). In light of these contradictory findings, it is important to consider that increased activation in the right hemisphere and frontal regions observed in these studies could represent various phenomena: compensatory mechanisms, less efficient processing, or perhaps the by-product of other cognitive or neurological factors, or the result of small sample sizes (10-20 participants per group on average). Furthermore, the heterogeneity of dyslexia implies that not all dyslexic individuals will necessarily exhibit the same brain activation patterns (see Ramus et al., 2018).

Word learning deficits in dyslexic children and adults have been reported in numerous behavioural studies (Aguiar & Brady, 1991; Di Betta & Romani, 2006; Elbro & Jensen, 2005; Howland & Liederman, 2013; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Vellutino et al., 1975). It appears that, compared to normal readers, dyslexic individuals show difficulties in phonological form learning when associating novel word with referents. This deficit seems specific to visual-verbal and verbal-verbal associations, with unimpaired performance for non-verbal associations, suggesting difficulties with phonological output underlying verbal word learning impairments (Albano et al., 2016; Kalashnikova & Burnham, 2016; Li et al., 2009; Litt et al., 2013, 2019; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). In a recent electrophysiological study, Rasamimanana et al. (2020) examined semantic compensation in a learning picture-word associations paradigm. Their results suggested that dyslexic students recruit more frontal resources than control participants when completing a word learning task and a following test phase semantic tasks in which participants were presented with newly leant words associated with semantically related or unrelated pictures and had to decide whether they were related or not. In addition, despite clear phonological impairments, dyslexic individuals reached similar levels of accuracy at the test phase semantic task to normal readers, suggesting that they use semantic knowledge to compensate for their phonological deficit. The ability to learn new words by the strategic use of semantic knowledge and context could explain why dyslexic students manage to achieve normal vocabulary size (Cavalli et al., 2016). However, note that these conclusions were based on a lack of significant between groups difference and should therefore be replicated, preferably with Bayesian analysis allowing for the detection of significant lack of statistical difference.

Overall, evidence presented in this section suggest that, by virtue of interactions between primary semantic, phonological, and visual systems, weak phonological skills could be compensated by semantic knowledge in dyslexia, as predicted by the primary systems hypothesis (Patterson & Lambon Ralph, 1999; Plaut et al., 1996). This compensatory mechanism has been primarily observed in reading tasks (e.g., Ben-Dror et al., 1991; Cavalli, Duncan, et al., 2017; Hennessey et al., 2012; Nation & Snowling, 1998), and preliminary evidence was found in word learning (Rasamimanana et al., 2020). To my knowledge, no studies have been conducted to examine if semantic compensation holds outside word reading or learning contexts. Therefore, the central aim of this thesis is to investigate semantic reliance in verbal short-term memory tasks in dyslexia, which has implication for phonological acquisition (Gathercole, Service, et al., 1999; Gathercole & Baddeley, 1989). Deficits in verbal short-term memory are present in children and adults with dyslexia (Avons & Hanna, 1995; Brady et al., 1983; Griffiths & Snowling, 2002; Kramer et al., 2000; J. Martin et al., 2010; Nithart et al., 2009; Pennington et al., 1990; Ramus et al., 2003; Roodenrys & Stokes, 2001; Snowling et al., 1996; Tijms, 2004a). They seem to arise from phonological difficulties (Ramus & Szenkovits, 2008), and since the primary systems account envisages interactions between semantic and phonological representations across tasks and modalities (Patterson & Lambon Ralph, 1999; Plaut et al., 1996; Savill et al., 2019), semantic effects were expected to emerge in immediate serial recall, particularly when phonological representations are weak or unstable. Notably, Savill et al. (2019) found that semantic effects were amplified when phonological skills were weakened in healthy adults, which suggests a continuous relationship between phonological skills and semantic effects in vSTM tasks. If similar patterns are found in the empirical work of this thesis, this would extend empirical support for models of vSTM that emphasise the interaction between semantic and phonological representations (Patterson & Lambon Ralph, 1999; Plaut et al., 1996; Savill et al., 2019).

1.7 Aims of the present research

This thesis primarily seeks to investigate the relationship between long-term linguistic knowledge and vSTM amongst both dyslexic and non-dyslexic adults. More specifically, the aims are as follows:

a) To scrutinise the impact of varied types of lexical-semantic information on vSTM.

b) To evaluate if the linguistic knowledge effects observed at the phoneme level persist and expand across various types of semantic information, in alignment with the semantic binding hypothesis.

c) To assess whether similar long-term linguistic effects impact adults diagnosed with dyslexia.

d) To investigate the potential occurrence of semantic compensation in vSTM tasks amongst individuals with dyslexia, as suggested by the primary systems hypothesis.

e) To explore whether semantic compensation is dependent on the type of semantic support at hand.

The remainder of this chapter will introduce the methodological approaches employed across the PhD programme of research to address these aims.

1.8 Experimental approaches

A common approach to assessing the contribution of semantic representations in vSTM is to use lists of words, and often nonwords, with different linguistic properties in immediate serial recall tasks. As previously mentioned (section 1.4), these properties can be lexicality (e.g., Hulme et al., 1991; Poirier & Saint-Aubin, 1996), lexical frequency (e.g., Roodenrys et al., 2000; Watkins & Watkins, 1977), and concreteness/imageability (e.g., Kowialiewski & Majerus, 2018; Walker & Hulme, 1999). The advantage of using existing words is that they benefit from established phonological, lexical, and semantic representations; being well established in LTM. Hence, this approach will be used in Chapters 5 and 6. However, it can be difficult to distinguish between the contribution of lexical-semantic properties and associated relative phonological familiarity with this type of stimuli. Addressing this issue can be effectively done through the use of word learning paradigms, as they allow for training nonwords with perfectly matched amount of phonological exposure.

Word learning paradigm as a means to assess semantic contribution to verbal short-term memory

In an attempt to assess an independent semantic contribution to vSTM, Savill et al. (2015, 2017) developed an original novel word learning paradigm. In this study, prior to testing in ISR, participants were phonologically familiarised with the nonwords that were either associated with a meaning or left without any associated meaning. More specifically, in the first phase of their nonword training task (after a semantic training phase familiarising participants with the to-be-trained semantic information), participants learnt the association between auditorily presented nonwords and either semantic information (i.e., an image and written descriptions of uncommon objects) or blurred images which did not contain semantic information. In the second phase, these newly learnt nonwords constituted ISR lists alongside entirely new nonwords that participants attempted to recall. Despite the likely superficial level of semantic representations and the possibility these were not well established in LTM, this manipulation was sufficient to find significant effects in vSTM. The influence of newly learned semantic representations became apparent immediately post-training, with no significant alterations noted after overnight consolidation.

However, it is important to mention that the complementary learning system model (CLS, Davis & Gaskell, 2009) anticipates that for the process of word learning a consolidation period is necessary for complete integration of words into the lexicon. To be more specific, the CLS model proposes a dialogue between hippocampal episodic memory and neocortical modules that leads to consolidated memories. Two learning mechanisms are identified, one fast-learning process supported by the hippocampus and another, slower neocortical learning which requires overnight sleep consolidation. Hence, an initial episodic stage followed by a lexical stage are identified to acquire new words. Episodic memory stores information about representations dependent on context, that can be learnt rapidly and stored immediately, and for the representations to become independent of the context, memory consolidation is needed. Nonetheless, the absence of consolidation effects found by Savill et al. (2017) appears to suggest that adults possess the ability to rapidly acquire new words. This process is often referred to as fast mapping (Carey, 2010; Carey & Bartlett, 1978; Shtyrov, 2011). Fast mapping involves the speedy association of words with their respective concepts, and the retention of these associations over time (Vlach & Sandhofer, 2012).

Drawing from these results, Chapter 2 and 3 are designed to examine the contribution of newly acquired linguistic representations to vSTM in dyslexic and non-dyslexic adults. These studies comprise a learning phase prior to ISR, to assess pure effects of lexical-semantic representations beyond phonological familiarity. In Chapter 2, electroencephalography (EEG) is used as an objective measure of learning to further examine the impact of lexical-semantic representations on novel (non)word acquisition (similar to Hawkins et al., 2015). This was a key objective of the present research program, which was put to one side for practical reasons (i.e., the closure of laboratories due to the COVID-19 pandemic) in subsequent chapters. Finally, in Chapter 4, a word learning paradigm was also employed, but this time nonwords were paired with existing English words that had different imageability levels. The intention was to mimic a more authentic method of learning new words, which typically involves associating unfamiliar words with existing words and their corresponding concepts.

Online research and reproducibility

Due to the unforeseen closure of the laboratories engendered by the Covid-19 pandemic, all studies except Chapter 2 study were specifically adapted and designed around being conducted online. One major advantage of web-based studies is the access to larger and more diverse samples of participants. A considerable amount of psychological lab-based research employs homogeneous convenience samples termed WEIRD (Westernized, Educated, Industrialized, Rich, Democratic, Henrich et al., 2010) consisting of students from western university which are not representative of the general population. These convenience samples are easy to reach but are also often non-naïve about psychological research procedures and paradigms which can result in biased results (Gagné & Franzen, 2023; Palan & Schitter, 2018) and can be fairly homogenous in terms of socioeconomic and educational background. Online recruiting platforms such as Prolific (www.prolific.co) allow for the recruitment of more representative and wide-ranging samples by virtue of their accessibility and was thus used in the present research. Another advantage of online research, and more specifically Prolific, is the simplification of the recruitment of hard-to-reach populations such as adults with dyslexia through the use of pre-screening criteria, allowing or rejecting participants from taking part in experiments (Palan & Schitter, 2018). According to Gagné and Franzen (2023) adding further checks by asking participants if they have been diagnosed with dyslexia helps to avoid participant fraud - suggestion that is implemented in the online research work of this thesis. Importantly, recruitment exclusion criteria need to be defined before starting the data analysis process (Gagné & Franzen, 2023; Nosek et al., 2018), and to this end can be pre-registered on a registry service such as the Open Science Framework (OSF) (http://osf.io) to increase reproducibility.

Overall, it seems Prolific yields good data quality compared to other platforms such as MTurk (Peer et al., 2022, but see also Litman et al., 2021), and previous research has demonstrated that results from lab-based experiments can be replicated online if relevant adjustments are considered (Gosling & Mason, 2015; Sauter et al., 2020; Stewart et al., 2017). The main concern when shifting studies online is a consequent data quality decline, due to the lack of control over the environment in which participants complete the experiment. Gagné and Franzen (2023) suggested solutions for mitigating the risks of online testing with dyslexic participants, such as implementing clear and detailed instructions, data screening measures, time limits, browser and device restrictions, fair pay, counterbalancing, and dyslexia screening with standardised tests, which should ensure good data quality. In addition, Prolific recommends using attention checks to ensure participants are reading instructions thoroughly such as the instructional manipulation task, whereby participants are explicitly instructed to "complete a task in a certain way, and are therefore designed to see whether or not a participant has paid attention to the question being asked" (Prolific Team, 2022). These recommendations as well as further adaptations (see method sections of the empirical chapters for more details) are applied in the online experiments in this thesis. The web-based experiment builder Gorilla.sc was chosen for designing and administering online experiments, since it allows for voice recording and benefits from good precision and accuracy (Anwyl-Irvine et al., 2020, 2021).

All chapters, excluding Chapter 2, were pre-registered on the Open Science Framework to enhance the transparency and accountability of the research procedures. The pre-registration links will be provided at the beginning of the respective chapters. It is important to highlight that a significant divergence from the pre-registered methodology was the implementation of Bayesian analyses in place of the originally intended frequentist analyses. This reflects the learning of this new methodology and the subsequent choice to reassess the data using this fresh outlook. This approach facilitates the potential dismissal or endorsement of the null hypothesis, a capability that traditional analyses lack (Shrout & Rodgers, 2018). According to Dienes (2016, p.60), Bayes factors "would help science deal with the credibility crisis, retain their meaning regardless of optional stopping, despite other tests being conducted, regardless of time of analysis [and] illuminate the benefits of pre-registration" (see also Dienes, 2014; Dienes & Mclatchie, 2018; Rouder, 2014; Schönbrodt & Wagenmakers, 2018).

In addition, JASP statistical package (JASP Team, 2022, Version 0.16.1) was used to perform statistical analyses, it is an open-source software program for statistical analysis that provides Bayesian statistical methods, which promotes transparency and accessibility in scientific research. Many proponents of Open Science advocate for such methods, as they can provide richer insights and avoid some of the pitfalls associated with p-value-based analyses.

1.9 Statistical approaches

Planned comparisons

The upcoming studies in this thesis involve a between-subject factor group (dyslexic versus non-dyslexic adults), which is used as such in Bayesian ANOVAs to investigate potential interactions between group and within-subjects variables. Additional Bayesian t-test analyses are performed with divided data from both the dyslexic and non-dyslexic groups. This approach enables the identification of effects specific to either the dyslexic or non-dyslexic group, even if a collective effect is not identified. This is a critical step in addressing the research questions posed in this thesis.

Immediate serial recall coding and analysis strategy

In all the chapters, immediate serial recall (ISR) responses were transcribed phoneme by phoneme. This allows for the monitoring of individual phonemes, which is crucial for analysis at the phoneme level, especially in the context of the phoneme binding hypothesis (Patterson et al., 1994), which emphasises the movement of phonemes.

This report details two tiers of analyses: those at the item level and those at the phoneme level. For studies employing a word learning paradigm (specifically, Chapters 2, 3, and 4), I relied on target-based analytical methods. This analysis typically involves comparing the recalled items to the target items on each trial; this analysis procedure provides insights into the overall accuracy and pattern of recall in terms of the original target items. This approach was appropriate since the immediate serial recall lists comprised solely nonwords, so the focus is on examining the accuracy of the recalled items in relation to the original target items. On the other hand, when real words were incorporated into the ISR lists (as in Chapters 5 and 6), a response-based coding approach was adopted. The experiments in these chapters adapted and extended previous studies and so used their same coding procedure. In response-based analysis, the focus shifts from the target items to the actual responses provided by participants. This analysis aims to examine the organisation and structure of the recalled items and codes responses in relation to their overlap with the original target sequence.

At the whole item level, the primary measures include the following: Correct in any position (CAP) which is essentially a free recall measure that capture items correctly recalled without considering serial order. Based on previous studies (like those by Poirier & Saint-Aubin, 1995), we adopted this particular measure as a performance indicator because it is believed to capture the impact of lexical-semantic information most sensitively in ISR. The reasoning behind this is that when individuals employ lexical-semantic representations to uphold or reestablish the phonological trace, they often fail to keep the original sequence position of the item intact.

The CAP measure encompasses items recalled in the correct serial position (CIP) which is sometimes referred to as ‘strict serial criterion’, and serial order errors (ORD) which represent items correctly recalled in the wrong serial position. Measuring both correct and incorrect positional recall allows for the distinction between item memory (remembering what was presented) and order memory (remembering the sequence in which items were presented). These measures (CAP, CIP, and ORD) are expressed as a percentage of total target items.

At the phoneme level, the semantic binding hypothesis postulates that lexical-semantic understanding aids in tethering phonemes together, thereby reducing the likelihood of phoneme migrations. These migrations occur when a phoneme is uttered in the wrong position but maintains the same syllable placement as the target phoneme. Consequently, the important measure at the phoneme level is phoneme migrations, expressed as the percentage of total phoneme recalled. This approach is used because phoneme migrations are dependent on the total number of phonemes produced, as identified by Jefferies et al. (2006). The analogous measure in response-based analyses is referred to as phoneme recombination errors.

Bayesian analyses

Bayesian statistical approach is exclusively used in this thesis to reduce Type-1 false error in frequentist statistics (Schönbrodt & Wagenmakers, 2018). Bayesian statistics allow for detecting evidence in favour of the absence of an effect which enables more confident interpretation of null results by determining the strength of the evidence. Bayesian inference computes values against or in favour of a given model which shows how more likely the data is under the alternative hypothesis (H_1) compared to the null hypothesis (H_0). Bayesian Factor (BF) is used to reflect the likelihood ratio of the effect of interest to other models. I used BF_{10} which determines the likelihood ratio for H_1 relative to H_0. A classification of strength of evidence (Lee & Wagenmakers, 2014, see **Figure 1.7**) provides guideline for Bayes Factor interpretation viewed as a continuous measure of evidence: BF_{10} of 1 provides no evidence, $1 < BF_{10} < 3$ provides weak evidence in favour of H_1, $3 < BF_{10} < 10$ provides moderate evidence, $10 < BF_{10} < 30$ provides strong evidence, $30 < BF_{10} < 100$ provides very strong evidence, and $100 < BF_{10}$ provides extreme evidence. On the other side of the spectrum, BF_{10} values < 1 provide evidence in favour of the null hypothesis: $0.33 < BF_{10} < 1$ provides weak evidence in favour of H_0, $0.1 < BF_{10} < 0.33$ provides moderate evidence in favour of H_0, $0.03 < BF_{10} < 0.1$ provides strong evidence in favour of H_0, $0.01 < BF_{10} < 0.03$ provides moderate evidence in favour of H_0, and $BF_{10} < 0.01$ provides extreme evidence in favour of H_0. For example, a BF of 20 in favour of the H_1 means that the data are twenty times more likely under H_1 than H_0. All analyses were performed using the default wide Cauchy prior distribution of $r = \sqrt{2}/2$ (Bouffier et al., 2022; Kowialiewski & Majerus, 2018).

Bayesian mixed ANOVAs, t-tests and correlations were computed using JASP statistical package (JASP Team, 2022, Version 0.16.1).

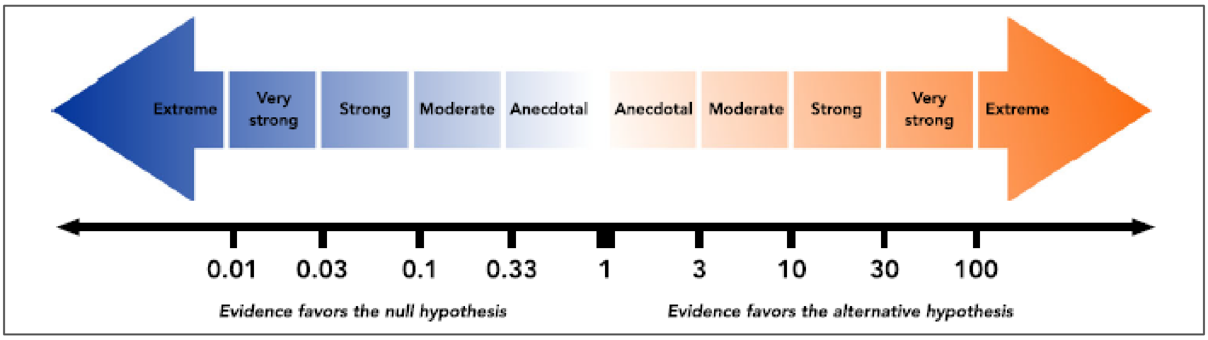


Figure 1.7. *Lee and Wagenmakers (2014) classification scheme for interpreting Bayes factors (BF_{10}). Taken from Quintana and Williams (2018).*

1.10 Chapter summary

This thesis primarily investigates the effects of long-term linguistic knowledge in verbal short-term memory in dyslexic and non-dyslexic adults. The key objectives include examining the impact of diverse semantic information on vSTM, investigating semantic compensation in vSTM tasks in dyslexic individuals, and determining the dependence of this potential compensation on the type of semantic support. These objectives lay the groundwork for the empirical research which will commence in the upcoming chapter.

Chapter 2.

On learning and recalling new words: the effect of phonological familiarisation and semantic representations in dyslexic and non-dyslexic adults.

2.1 Abstract

The contribution of long-term linguistic knowledge to verbal short-term memory is assumed to be grounded within the linguistic system by language-based accounts, with phonology and semantics playing a central role for language processing. However, the extent to which semantic representations provide core support in verbal short-term memory remains an open debate. In addition, as a consequence of interactions between primary systems, weak phonological abilities may result in greater reliance on semantic representations on a wide range of linguistic tasks, as predicted by the primary systems hypothesis. The aims of this study were to examine whether semantic representations constrain phonological processing independently of phonological familiarity by reference to manipulations of entirely controlled nonword stimuli, and to assess whether such semantic support is amplified in individuals with a diagnosis of dyslexia. Behavioural and electrophysiological measures were used to examine whether providing new phonological-lexical and semantic information supports the acquisition and maintenance of novel phonological forms in vSTM. Non-dyslexic and dyslexic participants were exposed to new spoken nonwords with or without semantic information, before completing tasks assessing verbal short-term memory through an immediate serial recall task (ISR) and passive auditory discrimination of a pair of trained nonwords (indexed by electrophysiological mismatch negativity responses; MMN). An advantage for phonologically familiarised, over entirely new nonwords, was expected, as well as an additional benefit for semantically associated forms (more word-like responses), and that such benefit may be more substantial for participants with weaker phonological

capacities (i.e., dyslexic participants). Results were partially in line with expectations: training (i.e., the availability of phonological-lexical representations) enhanced recall of nonword forms overall compared to entirely novel items. However, semantic associations conferred no further recall advantage. In addition, the MMN responses differentiated between the pair of semantically trained and phonologically familiarised nonwords in non-dyslexic participants only. Thus, evidence is compatible with phonological representations assisting maintenance of new phonological forms, but does not replicate an added semantic advantage on recall. Limited build-up of associated semantic representations via rapid learning may have compromised the establishment of semantic representations in long-term memory, preventing semantic support to arise in verbal short-term memory.

2.2 Introduction

Research over the past several decades has underscored the influence of linguistic representations on verbal short-term memory (vSTM) (Brener, 1940; Campoy & Baddeley, 2008; Hulme et al., 1991; Jefferies, Frankish, & Lambon Ralph, 2006b; Majerus & Van der Linden, 2003; Poirier et al., 1996; Romani et al., 2008; Tse, 2009; Watkins & Watkins, 1977). This influence is especially noticeable when comparing memory performance for words over nonwords (Brener, 1940; Hulme et al., 1991; Jefferies, Frankish, & Lambon Ralph, 2006b; Roodenrys & Hulme, 1993; J. E. Turner et al., 2000), high-frequency words over low-frequency ones (Gregg et al., 1989; Hulme et al., 1997; Roodenrys et al., 2000; Watkins & Watkins, 1977), semantically related words over unrelated ones (Kowialiewski & Majerus, 2018; Monnier et al., 2011; Poirier & Saint-Aubin, 1995; Tse, 2009), and concrete words over abstract ones (Acheson et al., 2010; Campoy et al., 2015; Kowialiewski & Majerus, 2018; L. M. Miller & Roodenrys, 2009; Romani et al., 2008). In interpreting the interaction between long-term stored linguistic representations and vSTM, divergent models have been proposed.

Traditional views, such as those based on the working memory model by Baddeley and Hitch (1974), suggest that long-term representations impact vSTM at the recall stage through a 'redintegration' process (Hulme et al., 1991; Schweickert, 1993b). More specifically, after phonological encoding of the items, degraded phonological traces are reconstructed through comparison to lexical-semantic long-term stored information at the moment of recall (see Chapter 1, section 1.5 for more details). On the other hand, language-based models propose a more intimate relationship between vSTM and the language system, with vSTM being viewed as the temporary or sustained activation of the language system (Acheson & MacDonald, 2009a; Majerus, 2013; N. Martin & Saffran, 1997; Patterson et al., 1994; Schwering & MacDonald, 2020, see Chapter 1, section 1.5). One perspective aligned with language-based models of vSTM, the semantic binding hypothesis (Patterson et al., 1994), posits that during language processing semantic and phonological information are intertwined, thus contributing to vSTM. This process helps to understand how semantic information contribute to vSTM, since the order of phonemes in vSTM might be shaped by semantic representations. That is, when a known word is encountered, the phonological system becomes accustomed to its phonological sequence and develops pattern completion properties. Co-activation with semantic representations provides the phonological system with additional stabilising input, reinforcing the pattern completion effect. Phonemes of familiar words are expected to be cohesively linked in recall, supported by the effect of semantic binding. In contrast, the phonemes of nonwords or unfamiliar words might exhibit a higher tendency to disassociate due to their lack of semantic ‘glue’, implying that they do not gain the benefits of semantic binding. Therefore, tracking phoneme movements, which refers to following the changes in speech sounds that make up words, is crucial in this context.

These contrasting interpretations become especially meaningful when considering language impairments. For example, the primary systems hypothesis (Patterson & Lambon Ralph, 1999) posits that, in cases of phonological deficits such as dyslexia, available support from semantic representations becomes especially important in a variety of language tasks. Neuropsychological studies with patients suffering from semantic dementia (Majerus et al., 2007; Patterson et al., 1994) and neuroimaging studies (Collette et al., 2001; Fiebach et al., 2007) provide compelling evidence for the supportive role of lexical-semantic representations stored in the language system in phonological maintenance in vSTM.

Furthermore, studies involving language-unimpaired participants have echoed this assertion of interactivity between phonological and lexical-semantic representations.

Nonword lists lack semantic support, and like words with degraded meaning in semantic dementia, healthy participants produce phonological errors when recalling this type of lists compared to words (Hoffman et al., 2009). In addition, when presented with mixed lists of words and nonwords, lexicality, word frequency and imageability influence recall of both types of items (Jefferies, Frankish, & Lambon Ralph, 2006b). Together these results suggest that lexical-semantic knowledge is central to phonological coherence. This becomes particularly salient when considering individuals with weaker phonological skills. General phonological performance (i.e., nonword recall performance) seems to somewhat predict the extent to which imageability supports vSTM, reading, and repetition, even in participants without language difficulties (Savill et al., 2019).

Building upon the existing body of evidence, the work in this chapter sought to apply the implications of the primary systems hypothesis to developmental dyslexia. Dyslexia presents a broad range of individual profiles, demonstrating varying degrees of literacy difficulties. These profiles, influenced by a combination of multiple and interrelated factors, frequently exhibit deficits in phonological processing (Liberman & Shankweiler, 1985; Ramus, 2003; Snowling, 1995) and vSTM (Brady et al., 1983; J. Martin et al., 2010; Pennington et al., 1990; Ramus et al., 2003; Snowling et al., 1996; Tijms, 2004b). Given these observations, it becomes compelling to probe the influence of linguistic representations on vSTM amongst adults with dyslexia, providing a useful lens through which to examine interactions within primary systems. The tendency for dyslexic individuals to exhibit poor phonological processing could prompt a protective effect of semantic representations on recall performance. Notably, although there has been considerable research highlighting the role of semantic involvement in reading within dyslexia (Hennessey et al., 2012; Nation & Snowling, 1998a; Plaut & Booth, 2000; van der Kleij et al., 2019; Vellutino et al., 2004a), the study of such effects in vSTM remains largely unexplored.

While it is widely accepted that semantic knowledge positively influences vSTM, several studies propose a diverging view (Benetello et al., 2015; Papagno et al., 2013). These studies suggest that phonological familiarity alone can account for influences on vSTM performance. For instance, in experiments where participants learned unknown words with or without associated meaning, increased recall performance was noted solely due to phonological familiarity and not from newly acquired semantic knowledge (Benetello et al., 2015). Similarly, Papagno et al. (2013) found comparable recall performance in semantic dementia patients for words with known phonological form but lost meaning, indicating that semantic representations may not enhance recall.

Nevertheless, as Savill et al's (2017) paper highlighted, these studies bear several methodological limitations, such as unequal phonological familiarity for all items or an excessive number of word repetitions, which is known to reduce lexical-semantic effects (Roodenrys et al., 2000). To explore the individual effects of phonological-lexical and semantic representations on vSTM, Savill et al. (2017) conducted an experiment where auditory nonwords were trained with or without (new) semantic information. They ensured phonological exposure was evenly distributed, and the number of trained nonwords for subsequent ISR tasks was sufficient to reduce item repetitions. In this study, participants learnt the associations between nonwords and blurred images (resulting in phonologically familiar nonwords without semantics) and nonwords with their meanings (using pictures of novel objects and their fictional associated properties). This experimental design enabled a direct comparison between phonologically familiar nonwords and phonologically familiar nonwords with associated meaning in ISR. It was found that phonological familiarity indeed enhanced recall compared to entirely new nonwords. Crucially, the association of newly acquired semantic representations had an additional, significant impact on recall performance, even at the phoneme level (fewer migration errors). These findings support language-based models of vSTM, suggesting that lexical semantic knowledge contributes to recall beyond just the effects of phonological familiarity.

Given these conflicting results and the limited research distinguishing the effects of phonological familiarity and semantic knowledge, the present study seeks to replicate the findings of Savill et al. (2017) using the same training procedure but also extends it to a sample of dyslexic participants and adds an implicit, neurophysiological measure: the Mismatch Negativity component (MMN); an event-related potential (ERP) response. The MMN is a negative deflection detected with electroencephalography that surfaces as a result of automatic phonological discrimination, typically brought about by a passive oddball paradigm where a low-probability deviant sound punctuates a steady stream of standard sounds (Näätänen et al., 1978). The MMN usually manifests between 100 and 200ms and is derived from subtracting the ERP generated by the standard sound from that elicited by the deviant sound. It allows for the independent scrutiny of acoustic change detection without the necessity for focused attention (Näätänen & Winkler, 1999; Pulvermüller et al., 2001). Linguistically, the MMN has primarily been used as a way to gauge the quality of phonological/nonword learning, but it can also act as an implicit measure of the influence of semantic associations on newly learned phonological forms (Aleksandrov et al., 2020; Hawkins et al., 2015; Shtyrov et al., 2019; Vasilyeva et al., 2019). Access to linguistic representations for spoken words is evidenced by amplified MMN responses for known phonemes and words as opposed to their unknown and nonword counterparts (Dehaene-Lambertz, 1997; Endrass et al., 2004; Korpilahti et al., 2001; Kujala et al., 2002; Näätänen, Lehtokoski, Lennes, & Cheour, 1997; Pettigrew et al., 2004; Pulvermüller et al., 2001; Sittiprapaporn et al., 2003). This measure has helped to demonstrate the adult brain capacity for rapidly acquiring new phonological forms (Sanders et al., 2002; Shtyrov et al., 2010), with lexical-semantic representations potentially aiding in forming novel neural memory traces. For example, Aleksandrov et al. (2020), found the MMN amplitude was larger for nonwords associated with high-frequency words than those associated with low-frequency words, suggesting lexical-semantic representations impact phonological processing. Hawkins et al. (2015) similarly suggested a direct impact of semantic information on the development of new phonological representations. They found an increased MMN response for nonwords associated with a visual semantic context compared to those without such semantic representations. This finding mirrors the connectionist and interactive models of word recognition that posit semantic knowledge as a significant aid to phonology (e.g., Plaut et al., 1996).

In order to control phonological-lexical exposure and examine the independent influence of semantic and phonological knowledge on vSTM, the current study commenced with a learning phase comprised of two sequential tasks, as per the methodology of Savill et al. (2017): a semantic training task and a phonological training task. These tasks were designed to establish associations between nonwords and their respective meanings, which would later be utilised in vSTM and learning measures. In the semantic training task, participants underwent an acquisition process, where they were familiarised with images of novel objects along with corresponding descriptions related to their context, function and mechanism, thereby acquiring semantic knowledge about these unfamiliar objects. To establish a visual control for later phonological familiarisation independent of semantic characteristics, meaningless blurred images were presented as frequently, leading to a condition termed 'phonologically familiarised'. Subsequently, in the phonological training task, sets of objects and blurred images were associated with nonword phonological forms. Nonwords tied to clear images constituted the 'semantically trained' condition, while nonwords tied to blurred images formed the 'phonologically familiarised' condition. Following the training phase, participants completed a series of standardised language and psychometric measures designed to assess their literacy and phonological abilities. These psychometric measures were divided between the first and the second day to ensure that testing did not exceed two hours per day.

On the first day, memory span and stability of the nonwords were assessed through an immediate serial recall task, where participants were tasked with recalling lists of semantically trained, phonologically familiarised, and new (untrained) nonwords. Furthermore, to gauge if the training effects extended to phonological access in a novel presentation modality and to augment previously observed semantic effects in reading, we employed a speeded reading task. Here, participants were instructed to read written forms of the semantically trained, phonologically familiarised, and new nonwords as quickly and accurately as they could.

The objectives of the second day were centred around assessing learning and phonological discrimination of the trained items. It started with a free recall task that measured the ability of participants to independently produce previously trained nonwords. Subsequently, employing an EEG oddball paradigm, MMN responses were recorded to a subset of semantically trained and phonologically familiarised monosyllabic nonwords, which were interspersed amongst phonologically similar known words, following the approach of Hawkins et al. (2015). This task provided a sensitive, implicit measure of the training effect on the phonological discrimination of newly learned items. Following this, a phonological discrimination task was administered to ascertain explicit recognition accuracy of phonological forms. This task determined whether nonwords from all exposure conditions (semantically trained, phonologically familiarised, and new nonwords) could be readily discriminated from phonological neighbours. Finally, the remaining half of the psychometric language tasks was administered.

It was predicted that:

1) A) If phonological representations were acquired after the training task, and if vSTM is supported by newly acquired phonological-lexical representations, *phonologically familiarised* nonwords should show a recall advantage relative to completely *new* nonwords. The predicted recall advantage for *phonologically familiarised* compared *to new* nonwords should translate in more items recalled in any position (with potentially more items recalled in the correct serial position and in the incorrect serial position).

   B) If phonological-lexical knowledge provides a source of constraint at the phoneme level, it is possible that better overall recall might be accompanied by fewer phoneme migration errors for the *phonologically familiarised* compared to *the new* lists.
2) A) On the condition that semantic associations were specified in long-term memory, the impact of semantic training was expected to provide an additional recall advantage when compared to *phonologically familiarised* nonwords.

   B) Less phoneme migration errors may also be observed in the *semantically trained* compared to the *phonologically familiarised* condition, based on the potential binding role of semantic representations (Jefferies, Frankish, et al., 2006; Patterson et al., 1994),
3) If newly acquired semantic representations facilitate phonological discrimination and the development of new phonological representations, a greater MMN response may be observed for *semantically trained* compared to *phonologically familiarised* nonwords both in the dyslexic and the non-dyslexic groups.

4) A) According to predictions from the primary systems hypothesis and language-based accounts of vSTM which posit that the interaction between lexical-semantic and phonological representations constrain phonological processing, weak phonological skills could result in a protective role of lexical-semantic representations. Thus, if dyslexic participants show overall phonological weaknesses, it could translate in relatively stronger effects of the semantic associations in vSTM and reading tasks (e.g., Hennessey et al., 2012; Vellutino et al., 2004). It should be noted here that, again, this effect is relying on the acquisition of the phonological forms and their associated meaning. Therefore, if dyslexic participants show a poorer level of learning after the training tasks than non-dyslexic participants, semantic compensation may not be observable.

   B) Furthermore, in relation to the prior point, there may exist a correlation between phonological abilities and the impact of semantic associations, as suggested by Savill et al. (2019).

2.3 Method

Participants

Thirty-eight adult participants, divided into two groups completed the study: 18 individuals diagnosed with dyslexia (average age = 22.72, SD = 5.73; 12 females) and 20 without dyslexia (average age = 24.75, SD = 6.36; 11 females). All participants were involved in a two-day testing session. Each participant had normal or normal-to-corrected vision and hearing. Participant recruitment was primarily conducted through York St. John University, utilising methods such as the student research participant panel and word-of-mouth referrals. All participants were compensated with £30 for their involvement in the study. The study was carried out with the approval of the York St. John University's Psychology Department Ethics Committee.

Psychometric Measures

Participants with a diagnosis of dyslexia were expected to show relative weaknesses of measures of phonological skills, working memory, reading, and spelling, but similar level of performance in non-verbal reasoning and semantic knowledge compared to non-dyslexic participants. Thus, participants' verbal and non-verbal skills were assessed with various standardised tasks.

Phonological awareness was assessed with the spoonerisms test from the York Adult Assessment Battery-Revised (Warmington et al., 2013). In this test, participants were presented with 12 names of renowned individuals and tasked with repeating them while transposing the initial phonemes of the first and last names (e.g., **M**ichael **J**ackson → **J**ichael **M**ackson). Additional measures of phonological awareness included the decoding efficiency (speeded word and nonword reading in 45 seconds) subtest of the Test of Word Reading Efficiency (TOWRE-2, Torgesen et al., 1999), the phonemic segmentation (which assesses the capacity to deconstruct a word into its component sounds and manipulate these sounds, e.g., say 'stream' without the 't'), and the rapid naming (assessing the amount of time required to identify and verbally name 40 outline illustrations presented on a page) subtests from the Dyslexia Adult Screening Test (DAST, Fawcett & Nicholson, 1998).

Semantic measures included the Warrington's Graded Synonyms task (Warrington et al., 1998), in which participants judge which of the two-word option presented on screen has the same meaning as a target word auditorily presented (e.g., target word: edifice, options: building / statue, correct response: building). There were 25 concrete target words (e.g., shed) and 25 abstract words (e.g., lucid) in the synonyms task. Additional semantic measures included the vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence II (WASI-2; Wechsler, 2011) in which individuals were asked to define a series of words. The words varied in difficulty and were presented both verbally and visually. The examiner rated the participant's responses based on criteria provided in the WASI-II manual. Responses were scored on a scale of 0-2, with 2 indicating a complete and accurate definition, 1 indicating a partial understanding of the word, and 0 indicating no understanding of the word or an incorrect definition. Participants were also administered the semantic fluency subtests from the Dyslexia Adult Screening Test (DAST, Fawcett & Nicolson 1998) in which they were asked to name as many words as possible from a specified semantic category (i.e., animals) within one minute.

The digit span task from the Weschler Adult Intelligence Scale fourth edition (Wechsler, 2008) was used to assess working memory. In this task, participants tried to repeat lists of numbers in the order of presentation. The task starts with a list of two numbers and list length increased up to 10 numbers, and there are two trials per list length. If participants failed to repeat the correct numbers on two consecutive trials, any further trials are discounted. The second block of this task consisted of backward recall of lists of digits.

Literacy skills related to reading and spelling skills were assessed with the word reading (participants were asked to read aloud a list of words that ranged from common and simple words to more unusual and complex words. The test started with simple, monosyllabic words and gradually progressed to more difficult, multisyllabic words) and spelling subtests from the Wide Range Achievement Test fourth edition; WRAT-4, (Wilkinson & Robertson, 2006). In the spelling subtest, participants were presented with a series of words orally and in the context of a sentence, and then asked to write (spell) them.

Finally, participants completed the matrix reasoning subtest from the WASI-2 (Wechsler, 2011) to assess non-verbal reasoning. In this task, participants were presented with a series of matrices or patterns with one piece missing. Each matrix was composed of several elements that followed a specific rule or set of rules. The participant's task was to determine the rule or pattern and select the missing piece from five options. Some of these tasks were computer-based and others were paper-based and coded online by the researcher.

Independent Bayesian t-tests were computed to compare psychometric scores of the dyslexic and non-dyslexic groups (see **Table 2.1**). On average, dyslexic participants performed poorer on phonological measures than non-dyslexic participants, with poorer accuracy at the spoonerisms test, the TOWRE-2 speeded reading for words and nonwords, and the DAST phonemic segmentation subtest. Relative weaknesses in working memory (digit span task), reading and spelling were also observed. As expected, results between groups did not differ for measures of non-verbal reasoning (WASI-2 matrix reasoning task), and semantic knowledge (semantic fluency subtest, Warrington's graded synonyms, and WASI-2 vocabulary test).

Table 2.1. *Psychometric measures of participants with and without dyslexia*

	Non-dyslexics (n = 20)		Dyslexics (n=18)		Bayes factor
	Mean	SD	Mean	SD	BF_{10}
Spoonerisms (max. score = 12)	10.52	1.69	9.06	2.55	3.07
TOWRE-2 speeded reading (age-scaled scores)					
Words	101.81	10.59	84.72	9.07	12593
Nonwords	112.00	9.39	89.89	9.27	$5.79*10^6$
DAST					
Phonemic segmentation (max. score = 12)	9.00	1.76	6.72	1.81	691
Rapid naming	26.81	3.50	28.78	3.78	0.14
Semantic fluency	26.33	5.12	24.11	5.85	0.63
Digit Span					
Forward (max score = 16)	10.3	1.87	8.22	1.26	157.51
Backward (max score = 14)	6.9	1.86	5.78	1.8	2.35
WRAT-4 (age-scaled scores)					
Reading	120.71	9.31	103.44	12.05	3088
Spelling	110.90	8.22	100.39	10.29	41.27
WASI-2 (age-scaled scores)					
Matrix reasoning	50.86	11.73	47.83	10.56	0.4
Vocabulary	62.48	8.00	57.22	5.92	2.82
Warrington's graded synonyms (max. score = 50)	33.90	5.81	32.61	3.85	0.41

Note. Bayes Factors (BF_{10}) > 3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect.

Stimuli

Training Task Stimuli

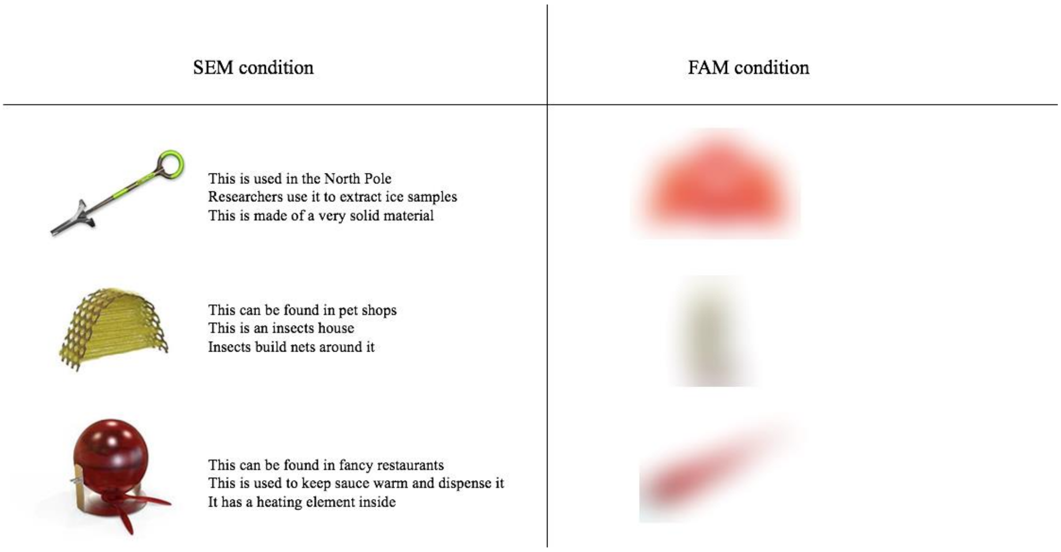
Nonword Stimuli

The stimuli set for the phonological training task consisted of 108 new spoken nonwords (with a CVCVC structure), which included 72 disyllabic nonwords that are not close phonological neighbours of English words (e.g., *fedoosh*; from Savill et al., 2017) and an additional 36 monosyllabic nonwords to accommodate nonwords suitable for the ERP paradigm (See Appendix A for the full list of stimuli). Monosyllabic nonwords were created based on known words (with a CVC structure, e.g., *boat*) to which the final phoneme was changed (e.g., *boag* and *boap*). All nonwords were designed to obey English phonology and phonotactic probabilities (biphone probabilities), which were matched between sets (calculated according to Vitevitch & Luce, 2004). Nonwords belonged to one of three sets of 24 disyllabic nonwords and 12 monosyllabic nonwords, which were allocated to the three training conditions (*semantically* trained: SEM, *phonologically* familiarised: FAM and *new*: NEW). The allocation of the nonword sets to their training condition was rotated across participants.

Nonwords were recorded by a British female speaker. The length the nonwords were normalised to 1000ms for the disyllabic items and 750ms for the monosyllabic items. Pitch was not altered, and intensity levels were normalised to 70dB with Praat software (Version 6.0.48).

Image Stimuli

In total, 36 images of unusual objects with background removed were sourced from the Internet (27 were taken from Savill et al., 2015 and 9 new images were selected following the same method). In the SEM condition, nonwords were associated with colour images of unusual objects and three definitions unique to the image describing the context in which the object can be used, its mechanism and its function (see **Figure 2.1** for an example). In the FAM condition, no meaning was attributed to the nonwords which were paired with blurred images. Finally, the NEW condition referred to words that were not trained and had no image or definition associated to them. These were used in the ISR, reading and phonological discrimination tasks only.



This is used in the North Pole
Researchers use it to extract ice samples
This is made of a very solid material

This can be found in pet shops
This is an insects house
Insects build nets around it

This can be found in fancy restaurants
This is used to keep sauce warm and dispense it
It has a heating element inside

Figure 2.1. *Example of semantically trained objects with their definitions that were separately presented across training trials (SEM condition) and familiar blurred objects presented without definitions (FAM condition).*

Immediate Serial Recall Task Stimuli

Fifty-four nonword lists, each composed of four disyllabic nonwords from the SEM, FAM, or NEW conditions, were used in the immediate serial recall task (ISR). The original structure and stimuli from Savill et al. (2017) were retained since lists were designed so that there were no repetitions of phonemes in a given syllabic position within a list. This design feature allowed for tracking phoneme migration errors to assess differences in phonological accuracy of nonword recall, and test whether results of Savill et al. (2017) replicated.

EEG Task Stimuli

A subset of six monosyllabic items was created specifically for the EEG task (a passive multi-deviant oddball paradigm). The stimuli consisted of one English word and two of the trained nonwords that differed only in their last phoneme: *yard* /jɑːrd/, *yart* /jɑːrt/, *yark* /jɑːrk/. A non-pulmonic consonant (/p/, /d/, /t/, or /k/) was crossed-spliced onto the final consonant of the known words. Items used in the EEG task were thus identical until the recognition point (at 666ms after the item onset), which meant that items were only differentiable at the onset of the final phoneme. This recognition point was used to time lock the triggers of the MMN during EEG recording (see Hawkins et al., 2015).

Phonological Discrimination Task Stimuli

An additional set of 108 nonwords was created to be included in the phonological discrimination task. This set comprised phonological neighbours of the 108 SEM, FAM and NEW nonwords; these differed from the presented stimuli by a single phoneme (following Savill et al., 2017, p.88 "*vaitag* /vetæg/ had the neighbour *vaitang* /vetæŋ/, but each neighbour could have been one of a multitude of alternatives, such as *baitag* /betæg/or *vottag* /vɒtæg/"). These were recorded and edited in the same circumstances as the spoken stimuli used in the training tasks.

Procedures

Semantic Training Procedure

The aim of this initial task was for participants to learn the association between 36 images of new unfamiliar objects and the description of their function, context, and mechanism. An image of an uncommon object was displayed on screen with two descriptions beneath it (one correct and one corresponding to another image), and participants were asked to choose which of the description corresponded with the image by pressing a key accordingly (SEM condition). The trials stayed visible on the screen until participants gave their response, and feedback on accuracy was shown for one second prior to the start of the subsequent trial. Participants were expected to learn the correct associations throughout this task by means of the provided feedback. Another set of 36 blurred images without descriptions were shown for at least two seconds, and only required participants to press any key to continue to the next trials (FAM condition). Each image was presented 9 times (3 presentations each of the function, context, and mechanism descriptions for the SEM images) in a pseudo-random order via E-prime 2.

Phonological Training Procedure

Immediately after the semantic training task, the clear (SEM) and blurred (FAM) images were repeatedly presented with the auditory form of associated nonwords. Each nonword was shown in a pseudo-random order, six times alongside the correct image and twice with incorrect ones. Before the sound of a nonword started, each image (whether clear or blurred) appeared on the screen for 500ms. Participants were then asked to identify whether the association was correct or incorrect by pressing one of two keys. The image remained on screen until key press following which feedback on accuracy was displayed for one second (see **Figure 2.2**). Participants were expected to initially guess the correct nonword-image associations, and to learn these associations by the provided feedback (“correct” for the correct responses and “incorrect” for the incorrect responses).

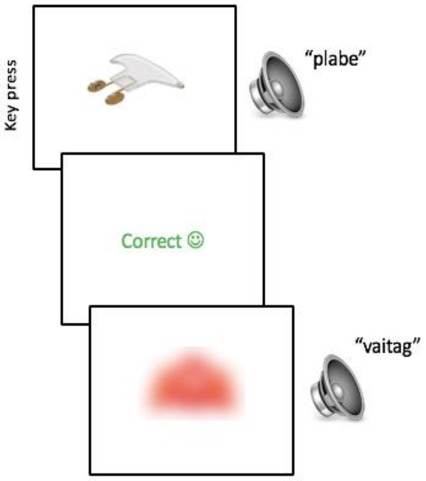


Figure 2.2. *Example trial the phonological training task. The first screen shows an image from the semantic training paired with an auditory nonword. Participants press a key to identify whether the association is the correct one or not and receive feedback on accuracy which allows them to learn the correct pairing. The last screen shows a FAM trial whereby a blurred image is associated with a phonological form.*

Learning throughout the two training sessions was assessed by changes in accuracy and reaction time to correctly identify whether the nonword was paired with the correct image. Better accuracy and shorter reaction times were expected over time as a result of learning.

Immediate Serial Recall Task

Following the completion of the psychometric measures (described in the participants section), participants completed an immediate serial recall task in which they were asked to repeat back in order lists of four disyllabic nonwords. The procedure for the ISR task and coding of responses was identical to Savill et al., (2017): There were 54 nonword lists derived from the SEM, FAM, or NEW conditions (18 lists per condition), presented in a fixed pseudo-random order. Participants listened to lists of four disyllabic nonwords presented at a rate of 1.25s per item through a headset whilst an exclamation mark was displayed on screen. After the auditory presentation of the nonwords, a question mark appeared on screen to prompt participants to recall the list they just heard in order. Participants were asked to produce the fullest response possible and to press a key to cue the next trial. There were three practice trials and three rest breaks throughout the task. Responses were digitally saved as separate audio files using E-prime 2 for later transcription.

Speeded Reading Task

The concluding task for the first day was a speeded reading task, an exploratory endeavour to discern the possible impact of the trained phonological-lexical and semantic representations on the speed and accuracy of reading. The written forms of the disyllabic nonwords —from SEM (semantically trained), FAM (phonologically familiarised), and NEW (untrained) conditions— were presented individually in a pseudo-random order. Each was displayed on the screen in lowercase white Times New Roman font against a black backdrop for a duration of 3000ms. Participants were tasked with reading these nonwords aloud as rapidly as possible. Their responses were digitally recorded as discrete audio files. Response latencies (i.e., reaction time) were then measured with CheckVocal software, and items were coded as correctly or incorrectly read by the researcher.

The objective of this task was to examine the potential complementary effect of the training on the reading performance, that is, whether newly acquired representations developed during the phonological and semantic learning phase could enhance the speed and accuracy of reading nonwords. In line with the objective of this experiment, it is important to clarify that while a potential improvement in reaction time and accuracy for FAM compared to NEW items, and for SEM compared to FAM nonwords was anticipated, these predictions were exploratory in nature.

Free Recall

As a direct assessment of participants' recall of the phonological forms of trained nonwords, they were given a two-minute time slot to verbally reproduce as many nonwords as they could recall from the training sessions. Responses were digitally recorded and phonologically transcribed to examine whether the availability of lexical and semantic representations benefit their phonological retrieval.

ERP Task – Passive Oddball Paradigm

A passive multideviant oddball paradigm designed to elicit a Mismatch Negativity response (Hawkins et al., 2015; Näätänen, Lehtokoski, Lennes, & Cheour, 1997) was used to assess phonological discrimination of the newly trained phonological forms, the day following exposure. The MMN response is assumed to reflect memory traces for phonemes (Dehaene-Lambertz, 1997; Näätänen, Lehtokoski, Lennes, Cheour, et al., 1997), and whole words (Pulvermüller et al., 2001; Shtyrov et al., 2010). Hence, this task provided an objective and implicit measure of new phonological form learning at a neural level. Semantically trained items were expected to elicit an enhanced neural response compared to the familiar nonwords.

Following Näätänen et al. (2004), a multifeatured oddball paradigm were used. Two deviant nonwords trained under SEM and FAM conditions were presented within a stream of a repeated standard English word (yard). The standard word was auditorily presented 1200 times and the SEM and FAM deviant nonwords (yark and yart) were presented 300 times with an 800ms SOA. This means that the probability of deviant occurrence was 25% amongst 75% of trials comprising the standard word. Two deviant nonwords were never presented in succession. Deviant nonwords were presented in a pseudo-random order to prevent participants from detecting a fixed pattern and predict the presentation of the deviant words which would potentially diminish MMN effects (Sussman et al., 2014). Since the elicitation of the MMN does not require focus of attention on the auditory stimuli, participants watched a silent video (Planet Earth II episodes form the BBC) while passively listening to the stimuli. The training condition of the respective deviant nonwords (SEM or FAM) was counterbalanced to avoid stimulus-specific effects.

Phonological Discrimination Task

By the end of the study, the ability to discriminate trained nonwords from their phonological neighbours assessed the precision of the acquired nonwords. In this task, participants were auditorily presented with nonwords that were either taken from the SEM, FAM or NEW conditions, or that were their respective phonological neighbours (differed by one phoneme in any position). For instance, the phonological neighbour of “thuddorg” was “muddorg,”. An exclamation mark was displayed on screen for 200ms, after which previously presented (SEM, FAM, or NEW) nonwords and their phonological neighbours were presented in a random order. Participants were asked to determine whether the nonwords were familiar (taken from the training tasks) or unfamiliar (i.e., phonological neighbours). Better learning of the nonword was expected to translate in faster and more accurate rejection of the trained items, and in slower and less accurate recognition of the phonological neighbours.

EEG Recording and pre-processing

Continuous electroencephalography (EEG) was recorded from 32 channels using actiCAP snap system during the oddball task (active electrodes, Brain Products GmbH, 2017) at 500 Hz sampling rate. The impedances were kept below 5 kΩ. The international 10-20 system at the frontal (Fp1, Fp2, F3, F4, F7, F8, Fz), central (C3, C4, Cz), temporal (T7, T8), parietal (P3, P4, P7, P8, Pz) and occipital (O1, O2, Oz) sites was used, with additional electrodes in the frontotemporal (FT9, FT10), frontocentral (FC1, FC2, FC5, FC6), centroparietal (CP1, CP2, CP5, CP6) and temporal-posterior temporal (Tp9, Tp 10) locations. Channels Fp1 and Fp2 were used to monitor for vertical and horizontal eye movements, the online reference were the mastoids and FPz served as the ground electrode.

The data were pre-processed and analysed in the Brain Vision Analyzer 2 (Brain Products GmbH, 2017). The signal was re-referenced offline to the left and right mastoids. EEG data were down-sampled to 250 Hz and filtered offline using a high-pass cutoff of 0.1 Hz to attenuate low-frequency noise and a low-pass cutoff of 30 Hz to attenuate line noise and EMG noise. The continuous EEG data were eyeballed for artefacts and bad channels were interpolated. The Independent Component Analysis (ICA) method was then used to identify and remove the artefacts related to eyeblinks. Continuous EEG data were sliced into epochs (i.e., time windows locked to stimuli presentation) from -100ms to 800ms with zero-point set to the recognition point, which corresponds to 666ms after the onset of the word, just before the last consonant which differentiate the SEM, FAM, and standard items. Epochs containing muscle movements, electrodes popping, and other artefacts were removed. Epochs were baseline corrected to -50 to 0ms before the relative disambiguation point which prevented from acoustic differences to contribute to the MMN (Shtyrov et al., 2010).

2.4 Data analysis

Immediate serial recall coding and analysis

Immediate serial recall coding

Participants' responses were phonologically transcribed and coded phoneme-by-phoneme to allow for tracking of the phoneme positions including phoneme migrations. The effect of previous exposure to phonological-lexical forms on vSTM maintenance was examined by analysing recall performance at the item and phoneme levels. Items were categorised as recalled in the correct serial position (item CIP – e.g., vaitag, kurrit → vaitag, kurrit), recalled in the wrong serial position (item ORD – e.g., vaitag, kurrit → kurrit, vaitag), or recalled in any position (item CAP corresponding to the combination of item CIP and item ORD). The potential stabilising effects of phonological-lexical representations were further considered at the phoneme level by examining differences in the rates of phoneme migration errors as a proportion of target phonemes (Jefferies, Frankish, & Lambon Ralph, 2006a). These errors correspond to phonemes recalled out of position that are not part of an entire item produced in the wrong position (e.g., **v**aitag, **k**urrit → **k**aitag, **v**urrit). Tracking phoneme level changes allows the possibility of identifying stabilising effects that may present at a sub-item level; and as proposed by language accounts envisioning interactive interaction of semantic and phonological representations, like the semantic binding hypothesis (Patterson et al., 1994).

Immediate serial recall analysis

The analysis of categorised responses began with an analysis of Correct in Position (CIP) recall performance of NEW nonwords as a baseline measure of vSTM, allowing for an evaluation without the influence of linguistic variables. Then, Bayesian mixed ANOVAs were computed. This involved considering the group (non-dyslexic vs. dyslexic) as a between-subject variable and the condition (FAM vs. NEW) as a within-subject factor. The purpose of this was to evaluate the effects of newly acquired phonological-lexical representation on the performance of item recall. The hypotheses are based on different relative effect sizes of training on recall in the dyslexic and non-dyslexic groups, so planned independent analyses of recall performance were also calculated for each group separately. Following this, recall analyses were carried out at the phoneme level, comparing phoneme migration errors in the FAM and NEW conditions.

In addition, to determine if newly acquired semantic representations had an additional impact on recall performance, the same Bayesian mixed ANOVAs and independent analyses were run, comparing the SEM and FAM conditions instead of FAM and NEW.

Lastly, the correlation between participants' phonological skills—established by averaging the z scores of the TOWRE nonword reading and spoonerism tasks, as per Savill et al., 2019—and the effect of phonological familiarisation and semantic associations was examined. This approach helped to reveal potential patterns or relationships between these variables. As per the primary systems account (Patterson et al., 1999), it is anticipated that participants exhibiting less proficient phonological skills would demonstrate more pronounced influences of semantic knowledge on recall.

Event-related potential data analysis

ERPs were analysed based on the linear derivation of FC1, FC2 and Cz (equivalent to the FCz electrode position, where amplitudes were maximal). MMNs were calculated as the difference waves between the voltage of the standard and the deviant (SEM and FAM) nonwords. The MMN was thus isolated from other components and reflected the discrimination between the standard and the deviant words (Bishop & Hardiman, 2010; Hawkins et al., 2015). The MMN peaked between 40 and 140ms and the average amplitude over this interval was submitted to statistical analysis.

First, Bayesian mixed ANOVA was computed with condition (SEM vs. FAM) as a within-subject factor and group (dyslexic vs. non-dyslexic) to analyse the impact of newly acquired semantic representations on phonological discrimination. Second, the condition effect was analysed in the dyslexic and non-dyslexic group separately. Third, the relationship between participants’ phonological skills (derived from the average of the spoonerism task and TOWRE nonword z scores) and the difference between the SEM and FAM MMN (i.e., the magnitude of the semantic training effect) was analysed.

2.5 Results

Behavioural data

Semantic training

By the end of the training, participants effectively learned the associations between the images and their meanings, achieving almost perfect accuracy (*M* = 95%, *SD* = 7%, see **Figure 2.3**). Accuracy and response time improved during the semantic training task, supported by decisive evidence (main effect of trial number on accuracy $BF_{10} = 5.2*10^{71}$, and on RT: $BF_{10} = 2*10^{115}$). There was no main effect of group on accuracy ($BF_{10} = 0.26$), suggesting that the dyslexic group and the non-dyslexic group showed similar learning effects across the task. Dyslexic participants were slower overall at responding with the correct associations than the non-dyslexic participants (main effect of group on RT; $BF_{10} = 4.85$).

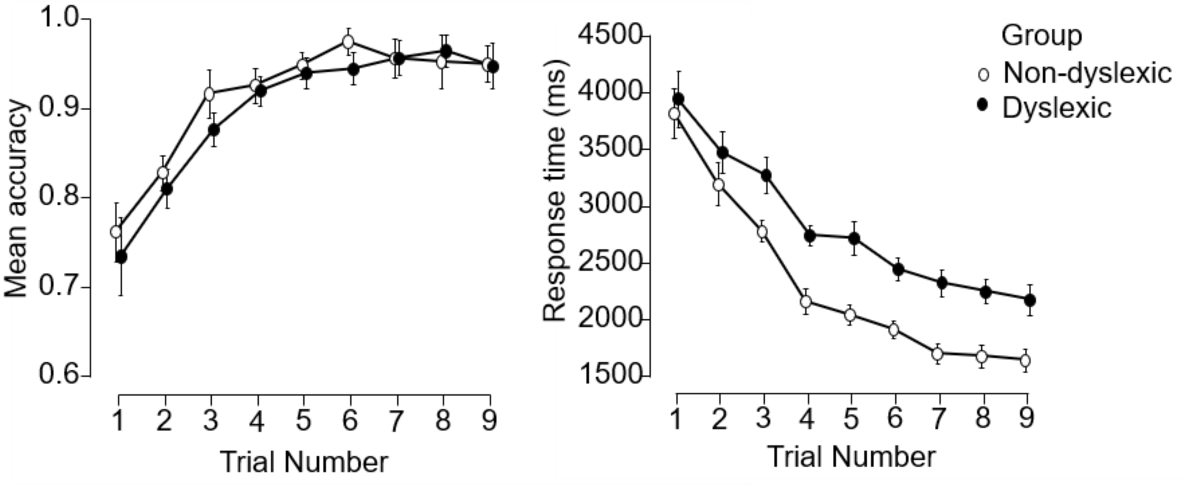


Figure 2.3*. Mean accuracy and response time at the semantic training task for the dyslexic and non-dyslexic groups.*

Phonological familiarisation training task

Accuracy and reaction times improved during the phonological familiarisation task, indicating that participants had reliably picked up the image-nonword pairings by the end of training (mean accuracy = 88%, main effect of trial number on accuracy: $BF_{10} = 3.6*10^{20}$, and on RT: $BF_{10} = 6.6*10^{25}$, see **Figure 2.4**). The image type (clear for the SEM condition and blurred for the FAM condition) impacted accuracy performance on this task (main effect of image type on accuracy: BF_{10} = 10618) with better performance, on average, for SEM image-nonword associations compared to FAM blurred images-nonword. Image type did not impact reaction time (BF_{10} = 0.28). There was an interaction for reaction time between the image type and trial number by which performance improved at a faster rate for the clear images (SEM) than for the blurred (FAM) images (BF_{incl} = 23.83). Similarly, an interaction between image type and trial number was found for accuracy, with better improvement for SEM images compared to FAM images (BF_{incl} = 25.75). Performance did not differ between groups (accuracy: BF_{10} = 0.26, RT: BF_{10} = 0.76).

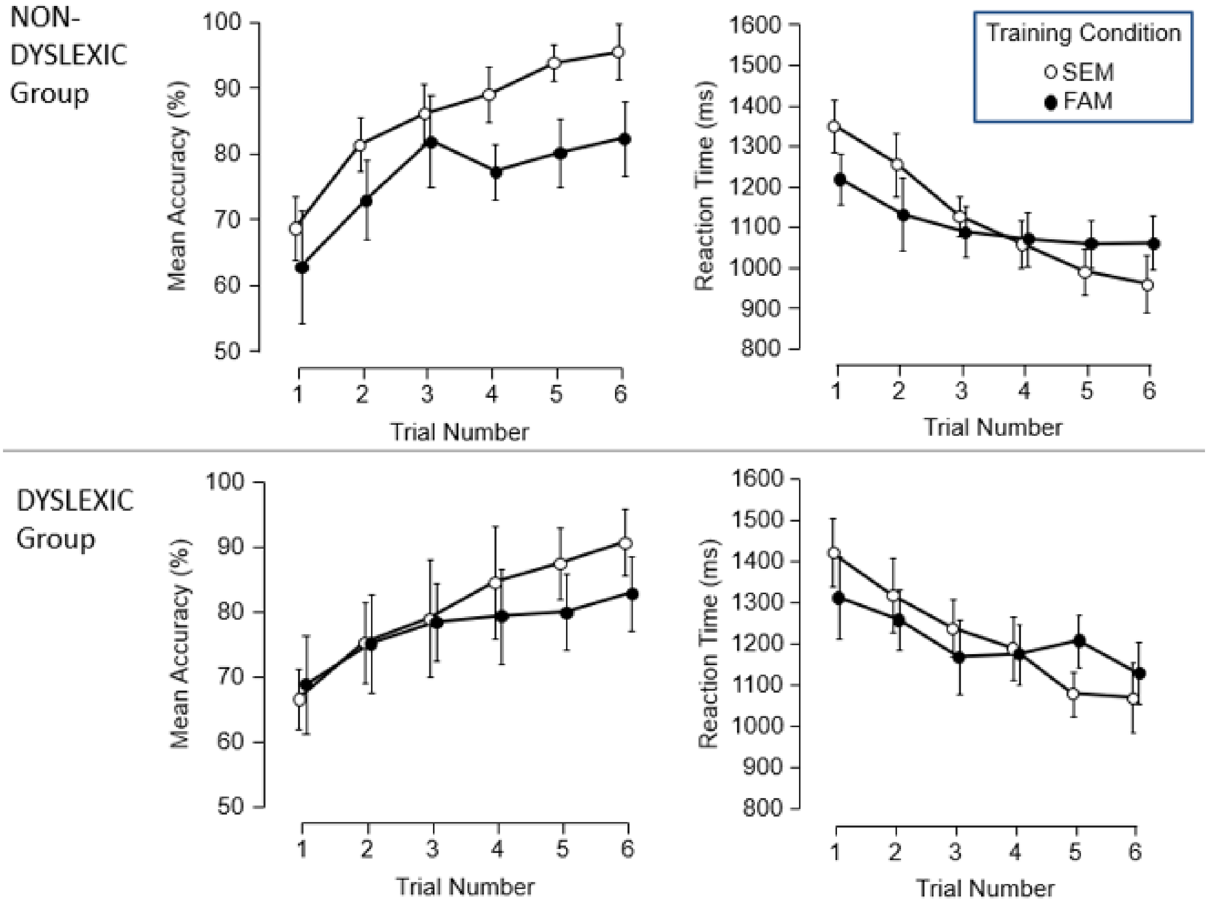


Figure 2.4. *Better recognition accuracy (recognition of pairings, left graphs) and reaction times (left graphs) during the phonological training task. The top panel illustrates the results for the non-dyslexic group, while the bottom panel presents the results for the dyslexic group.*

Free Recall

In both groups, participants independently recalled very few of the nonwords trained on the previous day (see **Table 2.2**). In the non-dyslexic group, four participants failed to produce any item at all, and three participants recalled only one SEM item correctly. When participants generated more than one item, they were more likely to be from the SEM than from the FAM condition (main effect of training condition: BF_{10} = 5.79). There was no main effect of group (BF_{10} = 0.41), and no interactions between training condition and group (BF_{10} = 0.59).

Table 2.2. *Average number of items produced in the free recall task in the SEM and FAM conditions for both dyslexic and non-dyslexic participants.*

Condition	Group	Mean	SD
SEM	Non-dyslexic	2.615	1.609
	Dyslexic	1.909	1.514
FAM	Non-dyslexic	1.308	.947
	Dyslexic	1.364	1.206

These results show that semantically trained items benefit from a slight recall advantage compared to phonologically familiar nonwords. However, due to the small number of items recalled, no strong conclusions can be drawn from the free recall task and is reported here for completeness only.

Immediate Serial Recall

Nonword recall baseline accuracy

Bayesian independent samples t-tests were computed to compare dyslexic and non-dyslexic participants recall accuracy (CIP) for NEW untrained nonwords. Descriptives statistics show that non-dyslexic participants recalled more NEW nonwords in the correct position compared to dyslexic participants (see **Figure 2.5**), and this difference was supported by weak evidence (BF_{10} = 2.35).

A recall advantage for newly acquired phonological representations?

Consistent with Savill et al (2017), prior phonological familiarisation with the nonwords showed an appreciable benefit to recall performance at the item level, as depicted in **Figure 2.5**: A significant increase was observed in items recalled in any position (CAP) from the familiarised (FAM) lists compared to the new (NEW) condition (BF_{10} = 21.69). No notable difference was found between the CAP recall performance of dyslexic and non-dyslexic participants (BF_{10} = 0.91), and no significant interaction was present between training condition and group (BF_{incl} = 0.56).

The advantageous effect of phonological familiarisation on items recalled in any position was primarily attributable to a higher frequency of correct serial position (CIP) recall in the FAM condition (M = 21.93%, SD = 8.96%) compared to the NEW condition (M = 19.04%, SD = 9.61%, BF_{10} = 6.4, see **Figure 2.5**). Evidence pointing towards an effect of group on items recalled in the correct serial position was very weak, where non-dyslexic participants exhibited slightly higher CIP recall rates than dyslexic participants (BF_{10}= 1.93). No significant interaction between group and training condition was detected for CIP (BF_{incl} = 0.68).

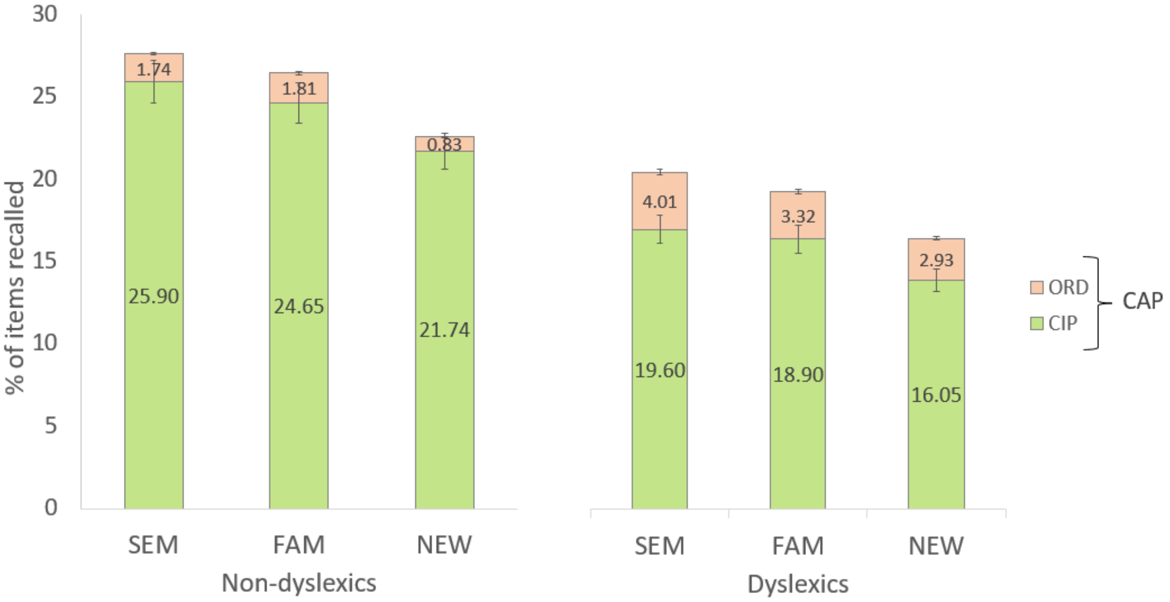


Figure 2.5. *Percentage of items recalled in any position (CAP) displayed by items recalled in the correct position (CIP) and item order errors (ORD).*

In general, items were infrequently recalled out of sequence (ORD) (M = 2.17%, SD = 6.34%), and the impact of the training condition on this outcome was quite weak (BF_{10} = 2.04). No significant effect of group was found (BF_{10} = 0.73), nor was there any interaction between group and training condition for items recalled out of sequence (BF_{incl} = 0.75).

Individual analyses of CAP recall performance for both dyslexic and non-dyslexic participants revealed that while dyslexic participants demonstrated a significant benefit from phonological training (BF_{10} = 9.52), the evidence supporting this effect in the non-dyslexic group was merely suggestive (BF_{10} = 1.63). Regarding items recalled in the correct serial position, the non-dyslexic group showed no significant influence of phonological familiarisation (BF_{10} = 0.82), and only weak evidence of such an effect was found in the dyslexic group (BF_{10} = 2.52). Meanwhile, order errors were influenced by training only in the non-dyslexic group (BF_{10} = 4.38), with the dyslexic group showing no such effect (BF_{10} = 0.32).

The findings at the phoneme level mirrored those at the item level: phonemes from familiarised (FAM) nonwords were less prone to migration than those from newly introduced (NEW) nonwords (BF_{10} = 20.24, refer to **Table 2.3**). No significant disparity was observed between dyslexic and non-dyslexic participants (BF_{10} = 0.63), and no interaction was noted between the group and training condition (BF_{incl} = 0.65). Upon conducting separate analyses for dyslexic and non-dyslexic groups, it was revealed that phonological training conferred benefits only to the non-dyslexic participants in terms of reduced phoneme migrations (BF_{10} = 6.5). In contrast, the dyslexic group did not exhibit any significant effect of training (BF_{10} = 0.92).

Table 2.3. *Mean percentages of phoneme migrations across different training conditions.*

	SEM	FAM	NEW
All participants	21.65 (11.08)	22.17 (8.75)	26.32 (12.54)
Non-dyslexic group	19.73 (9.55)	20.07 (7.34)	25.17 (12.12)
Dyslexic group	23.78 (12.49)	24.5 (9.77)	27.59 (13.22)

Note. Standard deviations in parentheses.

Overall, recall performance was positively impacted by the provision of phonological-lexical knowledge (FAM training). These newly acquired representations robustly helped items to be correctly recalled at the item and phoneme levels (replicating Savill et al., 2017 results).

Does the finding of a further impact of semantic representations on recall replicate?

There was no conclusive evidence in favour of an additional effect of semantic associations for all measures of recall (item CAP, CIP, ORD, and phoneme migrations – see **Table 2.4**). Bayes factors between 0.33 and 1 indicate weak evidence in favour of the null hypothesis (i.e., no evidence for an effect of the semantic training), results for this contrast were thus not worth exploring further. As can be seen in **Table 2.4**, dyslexics and non-dyslexics' performance did not differ for all measures.

Table 2.4. *Main effect results for group and training condition. The table shows Bayes factor values for items recalled in any position (CAP), items recalled in the correct position (CIP), items recalled out of sequence (ORD), and phoneme migrations (Phon. MIG).*

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error%
Null model (incl. subject)	0.20	0.39	2.56	1.00	
Item CAP					
Group	0.20	0.31	1.81	0.80	1.85
SEM vs. FAM	0.20	0.15	0.69	0.38	1.90
Item CIP					
Group	0.20	0.46	3.41	1.70	1.68
SEM vs. FAM	0.20	0.04	0.37	0.31	1.62
Item ORD					
Group	0.20	0.31	1.79	0.74	3.02
SEM vs. FAM	0.20	0.13	0.60	0.31	0.76
Phoneme Migrations					
Group	0.20	0.36	2.29	0.87	3.44
SEM vs. FAM	0.20	0.10	0.46	0.25	1.21

Note. P(M) = prior probability of each model; P(M|data) = model's posterior probability; BF = Bayes factor; BF_M = change from prior to posterior model odds; BF_{10} = Bayes factor of each model in comparison to the null model; error % = estimate of the estimation error of the BFs. Item CAP = item recalled in any position, Item CIP = item recalled in the correct position, Item ORD = items recalled out of sequence, SEM = semantically trained items, FAM = phonologically familiar items.

Relationship between phonological skills and training effects

Relationships between phonological skills and the effect of phonological familiarisation and semantic associations on items recalled in any position (CAP) were examined. A phonological score was derived from the average of the spoonerism task and TOWRE nonword z scores, and phonological familiarisation and semantic effects were indexed by the ratio between FAM and NEW CAP scores and by the ratio between SEM and FAM CAP scores respectively.

There was no relationship between phonological skills and the magnitude of the phonological familiarisation effect in ISR (r = 0.49, BF_{10} = 0.21, p = .77, see **Figure 2.6**, left panel), and no relationship between phonological skill and the semantic effect in ISR (r = 0.05, BF_{10} = 0.21, p = .75, see **Figure 2.6** right panel).

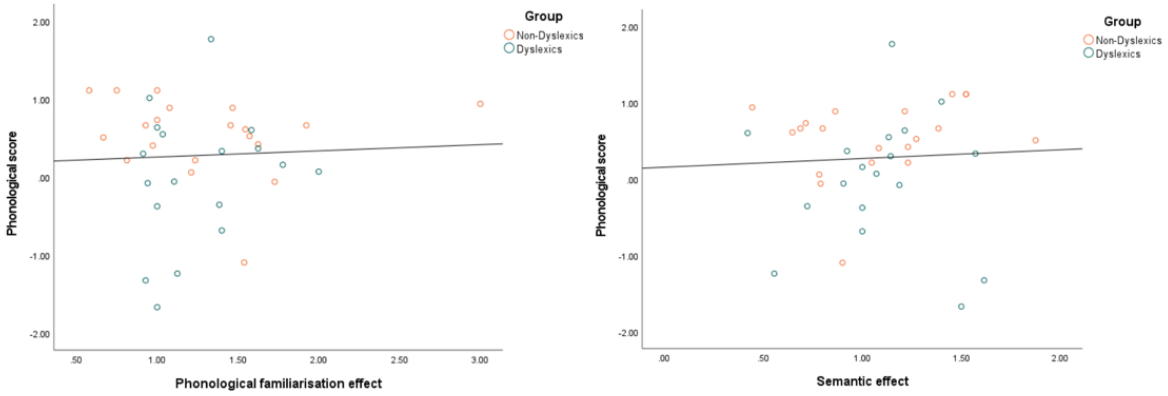


Figure 2.6. *Left graph: null correlation between phonological skills and the phonological familiarisation effect. Right graph: null corelation between phonological skills and the effect of semantic training in items recalled in any position at the ISR task.*

Phonological discrimination task

Bayesian mixed ANOVAs were computed to examine the influence of exposure conditions (SEM, FAM, NEW) on the identification of the nonwords and their differentiation from phonological neighbours. Improved discrimination was anticipated to result in quicker and more precise rejection of the learned items and in reduced speed and accuracy when recognising the phonological neighbours. Separate analyses were conducted for reaction times and accuracy for targets and phonological neighbours because contrasting outcomes for these items were anticipated.

As shown in **Figure 2.7**, the speed and accuracy with which nonwords were detected were influenced by the training condition (main effect of training condition on accuracy: $BF_{10} = 7.92*10^{15}$, and on RT: $BF_{10} = 8.95$). More specifically, discrimination improved for SEM compared to FAM nonwords (SEM vs. FAM: $BF_{10} = 3.63$), and there was decisive evidence in favour of an advantage for SEM and FAM items over NEW nonwords (SEM vs. NEW: $BF_{10} = 5*10^{9}$, FAM vs. NEW: $BF_{10} = 1.59*10^{8}$). Participants were faster at detecting SEM compared to NEW nonwords (SEM vs. NEW: $BF_{10} = 79.6$). However, reaction times did not differ between SEM and FAM nonwords (SEM vs. FAM $BF_{10} = 0.71$). Dyslexic and non-dyslexic participants reached the same level of accuracy and reaction times (accuracy: $BF_{10} = 0.26$, RT: $BF_{10} = 0.67$).

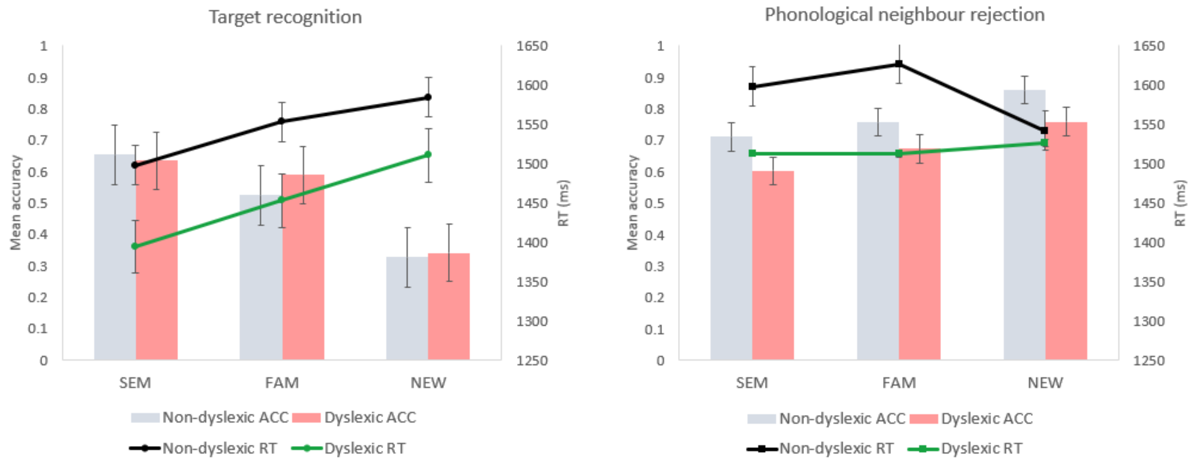


Figure 2.7. *Mean accuracy and rection time (RT) for target recognition and phonological neighbour rejection in the dyslexic and non-dyslexic groups. SEM = semantically trained nonwords, FAM = phonologically familiarised nonwords, NEW = untrained nonwords.*

D-prime values were used to determine sensitivity to SEM, FAM, and NEW items. There was a main effect of the training condition on D-prime accuracy ($BF_{10} = 7.12*10^{10}$). There was greater discrimination accuracy to SEM and FAM items compared to NEW items whereas SEM and FAM conditions did not differ (SEM vs. NEW: $BF_{10} = 3.21*10^{7}$, FAM vs. NEW: $BF_{10} = 244495$, SEM vs. FAM: $BF_{10} = 1.07$). There was weak evidence for a difference between groups, with non-dyslexic participants showing greater sensitivity than dyslexic participants ($BF_{10} = 2.17$). Overall, results of this task indicated that SEM and FAM items were recognised at a similar level towards the end of the second day.

For the phonological neighbours, rejection accuracy was impacted by training condition ($BF_{10} = 9.55*10^{6}$, see **Figure 2.7**). Rejection accuracy was better for NEW items compared to trained items (SEM vs. FAM: $BF_{10} = 2.96$; SEM vs. NEW: $BF_{10} = 6.03*10^{6}$; FAM vs. NEW: $BF_{10} = 634$), implying successful acquisition of trained items. The non-dyslexic group outperformed the dyslexic group (main effect of group on accuracy: BF10 = 10.35). However, the training condition did not influence response times ($BF_{10} = 0.2$). There were no interactions between group and training condition for accuracy ($BF_{incl} = 0.58$), and for reaction time ($BF_{incl} = 0.14$).

Speeded reading task

Bayesian mixed ANOVAs were computed with training condition (SEM vs. FAM vs. NEW) as a within subject factor, and group (dyslexic vs. non-dyslexic) as a between subject factor for reading accuracy and reaction time. There was weak evidence in favour of an effect of group on reading accuracy (BF_{10} = 2.08) with non-dyslexic participants showing better accuracy levels than dyslexic participants (see **Figure 2.8**). Training condition did not affect reading accuracy (BF_{10} = 0.59), and there was no interaction between group and training condition (BF_{incl} = 0.15).

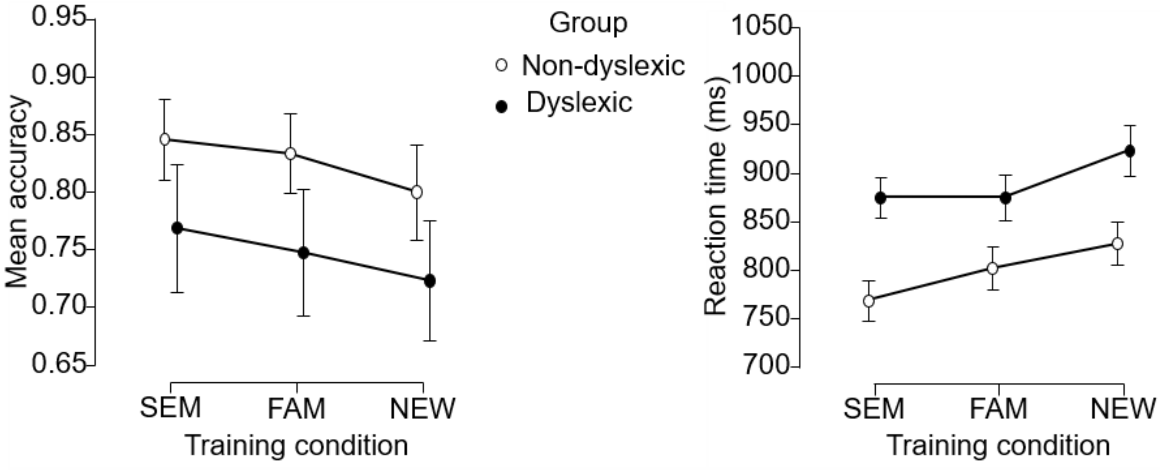


Figure 2.8. *Mean reading accuracy and reaction time across training conditions for the dyslexic and non-dyslexic groups. SEM = semantically trained nonwords, FAM = phonologically familiarised nonwords, NEW = new untrained nonwords.*

There was decisive evidence in favour of an effect of training condition on reaction time (BF_{10} = 1291), post hoc comparisons showed that SEM and FAM nonwords were read faster than NEW nonwords (SEM vs. NEW: BF_{10} = 1877; FAM vs. NEW: BF_{10} = 11.68), however, there was no difference between SEM and FAM nonwords (BF_{10} = 0.7). There was very weak evidence in favour of an effect of group (BF_{10} = 1.3), and no interaction between group and training condition for reaction time (BF_{incl} = 0.55).

Independent analyses of the difference between SEM and FAM nonwords in each group revealed a weak reaction time advantage for SEM over FAM nonword in the non-dyslexic group (BF_{10} = 2.01), and no differences between these training conditions for accuracy (BF_{10} = 0.27). In the dyslexic group, no significant differences between SEM and FAM nonwords were found (ACC: BF_{10} = 0.29; RT: BF_{10} = 0.25).

Electrophysiological data

The impact of the trained semantic association on early phonological discrimination was examined with Bayesian repeated ANOVAs with a within-subject factor condition (comparing difference waves for the SEM and FAM deviant nonwords), and group (dyslexic vs. non-dyslexic group) as a between-subjects factor. Bayes factors indicated a moderate effect of condition whereby FAM nonwords elicited more negative responses than SEM nonwords (BF_{10} = 3.72, see **Figure 2.9**). There was no effect of group (BF_{10} = 0.85), and no interaction between group and training condition (BF_{incl} = 0.61).

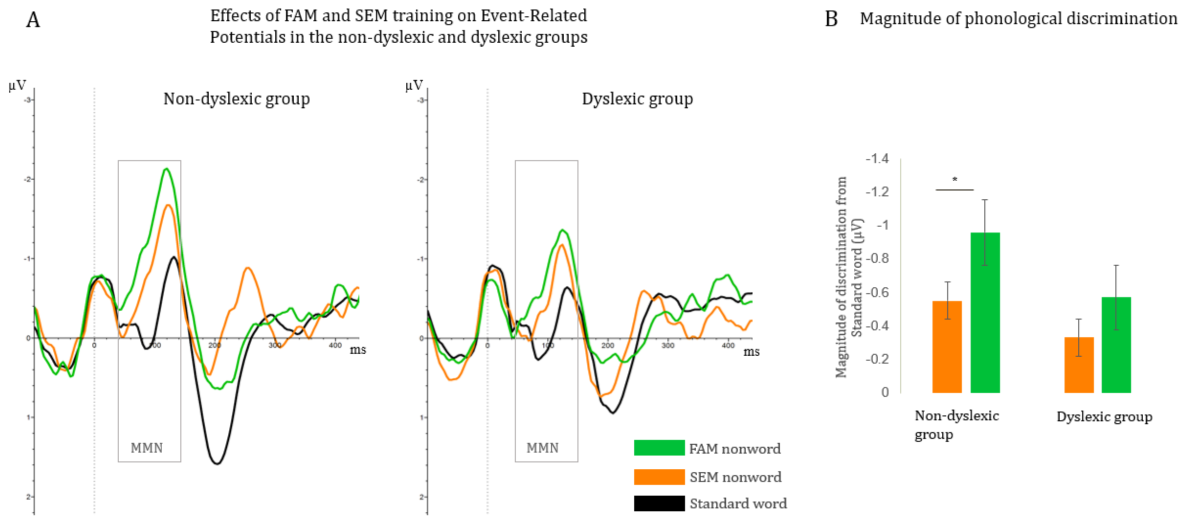


Figure 2.9. *ERPs illustrated for the FCz electrode in the non-dyslexic group and the dyslexic group. The black line represents the ERP response for the standard word (i.e., "yard"), the green and the orange lines represent phonologically trained and semantically trained nonwords respectively. The dotted line corresponds to the recognition point. Panel (B) shows the difference amplitudes for the SEM and FAM words from the standard word*

Planned analyses of the data from the non-dyslexic and the dyslexic group showed the difference between SEM and FAM nonwords was supported with moderate evidence for the non-dyslexic participants only (main effect of condition in the non-dyslexic group: BF_{10} = 4.1, and in the dyslexic group: BF_{10} = 0.54; see **Figure 2.9**).

Finally, the relationship between participants' phonological skills (derived from the average of TOWRE nonword and spoonerism task z scores, as per Savill et al., 2019) and the difference between the FAM and SEM MMN (i.e., the magnitude of the semantic training effect) was examined. There was no evidence in favour of a relationship between phonological skills and SEM MMN amplitudes (r = -.29 p = .08; BF$_{10}$= 0.86; see **Figure 2.10**).

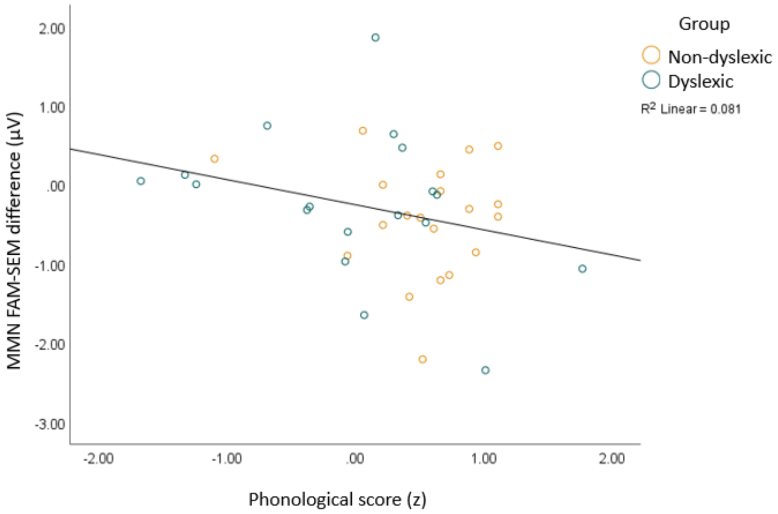


***Figure 2.10**. Relationship between the magnitude of the semantic training effect on MMN amplitudes phonological z scores. More positive values indicate larger MMN (i.e., better discrimination) for the SEM item, whereas more negative values indicate better larger MMN for the FAM item.*

2.6 Discussion

This study sought to ascertain whether the introduction of new semantic information aids in the acquisition and retention of novel phonological word forms within verbal short-term memory for both dyslexic and non-dyslexic adults, and to assess if these effects manifest differently between these groups. The hypothesis was that measures of verbal short-term memory would indicate a relative advantage for phonologically familiarised and semantically associated forms over new untrained nonwords, reflecting more word-like responses - a prediction in line with previous findings (Savill et al., 2017). Additionally, it was hypothesised that any effects of semantic associations on vSTM might be more pronounced, or of a similar magnitude, for participants with comparatively weaker phonological abilities, specifically those in the dyslexic group.

Enhanced responses to new phonological-lexical representations

Behavioural measures revealed a strong impact of the availability of phonological-lexical representations on vSTM. Even after only short exposure to auditory nonwords, dyslexic and non-dyslexic adults demonstrated a recall advantage for FAM nonwords over NEW untrained nonwords, resulting in better performance in all tasks. More specifically, in the ISR task, when participants recalled lists of either phonologically familiar nonwords or entirely new nonwords, more items were produced in the correct position, and phonemes tended to bound together for familiar nonwords. The advantage for familiarised phonological forms over new unfamiliar items is coherent with the argument that vSTM is a language-dependent system, interacting with speech production and speech perception (Jacquemot & Scott, 2006). Phonological sequences activated together during training became associated in the phonological system, allowing phonemes to be subsequently recalled in the correct order in vSTM. These findings mirror the results observed by Savill et al. (2015), which highlighted an advantage in short-term recall for familiarised nonwords associated with clear or blurred images. This clear advantage for familiar phonological forms over new unfamiliar items emphasises the integral role of familiarity in vSTM performance.

Electrophysiological results seemed to corroborate overall behavioural findings with a significant enhancement of the MMN responses elicited by the phonologically familiar nonword deviants. This potentially indicated an improved auditory discrimination of phonological contrasts given that the magnitude of MMN is affected by phonemic and lexical variations between the standard and the deviant stimuli, as well as phonological representations (Dehaene-Lambertz, 1997; Näätänen et al., 2007; Shtyrov & Pulvermüller, 2007; Winkler et al., 1999). For instance, a larger MMN amplitude was observed when a deviant native vowel was interspersed amongst standard non-native language vowels compared to a deviant language-native vowel (Näätänen, Lehtokoski, Lennes, Cheour, et al., 1997). Similar findings have been reported in infants and children across various languages (Cheour et al., 1998; Dehaene-Lambertz, 2000; Dehaene-Lambertz & Baillet, 1998; Shafer et al., 2004), as well as in the comparison of words versus nonwords (e.g., Pulvermüller et al., 2001).

However, a limiting factor on interpretation of the familiarisation effect on the MMN is the absence of new untrained nonwords in the oddball paradigm, since the effect of phonological familiarisation could simply index phonological deviancy without the comparison with a new untrained nonword. An untrained oddball condition was not included in the present study due to the number of additional trials that would have been required to keep the oddball ratios low, and because the key comparison was for FAM vs SEM. However, future studies incorporating all three types of nonwords (i.e., SEM, FAM, and NEW) would enable direct comparisons of MMN amplitudes (Näätänen et al., 2004). If a larger MMN indeed signifies better discrimination and access to long-term linguistic knowledge such as phonological, lexical, and semantic representations, then new untrained nonwords could elicit a smaller MMN response. An alternative interpretation of the increased MMN amplitude for the FAM deviant could be that a larger MMN corresponds to more distinct, salient contrasts, suggesting that NEW deviants would elicit a larger MMN response than FAM deviants.

Even though no interaction was found between group and the effect of phonological familiarisation on vSTM recall, independent group analyses revealed a distinctive pattern between dyslexic and non-dyslexic participants in terms of how phonological familiarisation impacts vSTM recall. For the dyslexic participants, the effect of phonological familiarisation was evident in improved recall accuracy, supporting the contribution of phonological-lexical knowledge to recall capacity. However, this familiarisation effect did not improve their recall of the order of the items and rates of incorrectly ordered phonemes, unlike the non-dyslexic group. This implies that, although they can help confident recall of some items, dyslexic participants may still struggle with sequencing or the temporal aspect of memory across a whole sequence (Majerus & Cowan, 2016). Non-dyslexic participants showed improvements in item and phoneme order recall after phonological familiarisation, indicating that phonological-lexical representations supported recall of the sequence or order of information. However, this was restricted to this fine-grained level; phonological training did not have a significant influence on their overall recall accuracy, which may be due to their developed phonological skills that did not require further enhancement from the familiarisation process. One interpretation of these results is that dyslexic participants could be relying more upon strategic and reconstructive recall processes than their non-dyslexic counterparts. If the strategic reconstruction of the phonological trace is executed through the selection of lexical candidates, it would conceivably influence the likelihood of correctly recalling words, but would not necessarily alter the incidence of phoneme migrations.

Intriguingly, electrophysiological data did not align with the expected trend based on a recent meta-analysis on auditory processing deficit in dyslexic individuals and associated MMN effects (Gu & Bi, 2020). While this meta-analysis indicated that dyslexic individuals, both children and adults, consistently exhibit attenuated MMN due to difficulties in speech perception and imprecise phonological representations, our data showed no such difference in the overall MMN response between the groups. This finding could indicate that, despite dyslexic individuals' potential difficulties with phonological processing (as evidenced by poorer performance at psychometric phonological measures), neural indices of discerning phonological deviations indicate that they remain relatively unimpaired. In the present study, dyslexic participants demonstrated a sensitivity to phonological deviancy on par with their non-dyslexic counterparts, suggesting that their capacity for such discrimination was preserved. This is an important detail to note, as it could suggest that the MMN, in this context, may not be indexing long-term phonological effects to the extent we might have initially anticipated (Shtyrov et al., 2010).

To probe the correlates of the MMN response, an additional analysis was carried out (Ylinen et al., 2019). This analysis revealed a correlation between the raw amplitude of the FAM deviant MMN and phonological skills in the dyslexic group, but not in the non-dyslexic group (see Appendix B). Dyslexic individuals seem to have a wider range of phonological abilities compared to non-dyslexic individuals, potentially leading to more variability in their responses. This variability could provide a broader base for correlations, such as the one observed between MMN amplitude and phonological skills. The MMN response is thought to reflect the brain’s automatic detection of acoustic deviance based on a neural representation of the regularities in the auditory environment. In the context of dyslexia, the MMN could be particularly sensitive to variations in phonological skill levels. However, it is important to note that while these possibilities might help explain the observed correlation in dyslexic individuals, the absence of such a correlation in non-dyslexic individuals is also significant. It suggests that other factors, potentially beyond phonological skills, contribute to the MMN response in non-dyslexic individuals. This could include long-term linguistic representations (potentially reflecting the effect of training), or a ceiling effect where phonological skills are already well-developed and thus do not show variation correlated with MMN amplitude. These interpretations, while plausible, remain speculative. Future research is necessary to further explore the MMN response and its relationship to long-term phonological representations and associative learning in dyslexic individuals.

On the absence of a semantic association advantage on nonword ISR

Explicit and implicit measures showed a benefit for phonologically familiarised items but the emergence of a further benefit of meaning-related knowledge was not detected in vSTM. Previous research found an effect of semantic representations in vSTM, whether these representations were already established (such as the manipulation of word imageability, Acheson et al., 2010; Bourassa & Besner, 1994; Campoy et al., 2015; Jefferies, Frankish, et al., 2006b; Majerus & Van der Linden, 2003; Miller & Roodenrys, 2009; Romani et al., 2008; Savill et al., 2019; Walker & Hul me, 1999), or fabricated through a training task (Savill et al., 2017). Such findings can be interpreted within the view that, phonological-lexical and semantic representations directly interact to support information in vSTM (i.e., semantic binding hypothesis, Patterson et al., 1994).

However, in the ISR task, neither the non-dyslexic nor the dyslexic group showed additional effects of newly acquired semantic representations in vSTM, deviating from results observed by Savill et al. (2017) in the context of newly trained meaning associations. The lack of a semantic recall advantage is not unprecedented and aligns with the findings from similar studies (Benetello et al., 2015; Papagno et al., 2013). For instance, Benetello et al. (2015) demonstrated that phonological familiarisation with Croatian words was sufficient to yield a recall advantage in ISR, with no additional advantage observed when these words were also associated with meanings. Thus, our findings, in alignment with this latter group of studies, seem to underscore the potency of phonological familiarisation in vSTM recall, potentially without significant contributions from additional semantic associations.

Perhaps most relevant for interpretation of these results, examining effects of semantic information in the ISR task relied on the establishment of those semantic representations and lexical associations, and maintenance of those associations in long-term memory following training. It is important to consider how effectively this may have been achieved. Following the complementary learning system account of word learning

(Davis & Gaskell, 2009) it seems likely that the pattern of results could, at least in part, be due to poorly established semantic representations and/or associations between the nonwords and semantic information. According to this account, novel words are acquired through two stages: a fast, initial acquisition supported by episodic memory (medial temporal and hippocampal learning), and a slower lexical-semantic integration through neocortical learning and consolidation. Therefore, new word forms without associated visual information could be rapidly integrated to the phonological lexicon, without the need for overnight consolidation to be cortically represented; whereas for development of the semantic information associated to the new word such as a visual referent, consolidation may be required for cortical establishment (Takashima et al., 2014). This could offer one explanation for an advantage for phonologically familiarised nonwords in the ISR task with no additional benefit of semantic information, since the task was completed on the training day in the present study as well as in Benetello et al. (2015). In addition, even though an advantage for *semantically trained* nonwords was found in the free recall task, overall poor performance at this task suggests that the nature of the trained semantic representations may have lacked richness, potentially reducing the effectiveness of the semantic-phonological associations.

At odds with the complementary learning system explanation and/or limitations of the semantic training itself, Savill et al. (2017) found a semantic benefit on vSTM with and without a consolidation period, using the same type of stimuli. On that basis, the current study followed Savill et al's design. However, twelve monosyllabic nonwords were added to the training task in the present study compared to the replicated paradigm (Savill et al., 2017), resulting in 72 nonwords to learn in the training task. These were determined to be necessary for subsequent use in the EEG task, and although not all monosyllabic nonwords were used in this task, training a sufficient number of monosyllabic items allowed for the critical pair not to protrude compared to the disyllabic items. However, the resulting number of nonwords might have been excessive, given the brief period of training, and especially for dyslexic participants. Most word learning studies use a smaller set of stimuli (i.e., between 6 and 40 items), with longer learning phases, and more exposure to the new words (e.g., 16 exposures to 12 items in Clay et al., 2007; 40 exposures to each 12 nonwords in Hawkins et al., 2015; 22 exposures to 10 items in Kapnoula et al., 2015; 96 exposures to the 12 items in Leach & Samuel, 2007). In the present study, auditory nonwords were presented six times with the correct picture and twice with a random picture, as it was replicating the conditions of Savill et al. (2017). The restricted exposures might have limited in-depth learning of the nonwords and their associated meaning, as suggested by poor free recall task performance – in spite of an average of 93% accuracy for the SEM nonwords by the end of training – which was comparable to Savill et al. (2017).

In addition to potential issues with the strength with which links between the phonological-lexical forms and semantic information may have been forged, it is worth reflecting on the quality and validity of the representations trained as a proxy for long-term semantic knowledge. Meaning associated with the nonwords was artificially constructed (i.e., an image of an unfamiliar object associated with three fictional properties of a novel object) and was therefore not pre-established in long-term memory. A strength of this training paradigm was that it allowed for perfectly matched phonological exposure to the nonwords trained with and without semantic information, as well as controlled semantic 'knowledge'; with equal exposure to the semantic representations constructed for each nonword and no competing preexisting lexical-semantic label. The rationale is that this would serve to reduce differences in conceptual similarity and experience between participants, and aid interpretation of subsequent semantic effects (e.g., independently of individual availability/frequency). However, new semantic representations may not have been fully formed and embedded into long-term semantic networks after training due to poor quality and superficiality of the developed representations, and/or perhaps because of limited time available between training and the ISR task.

Given that, on the second day, recognition of the trained nonwords were similar between the semantically trained and phonologically familiarised items in the phonological discrimination task, *semantically trained* and *phonologically familiarised* nonwords seemed, by that stage, to be equally specified in long-term memory. Therefore, an additional ISR task on the second day would have helped to clarify whether the lack of a semantic effect in the present study was due to the absence of a consolidation period, which might prevent the development of semantic representations. Alternatively, the issue could arise from inefficient training of the associations between nonwords and multidimensional object information, potentially caused by too many nonwords to learn without sufficient exposure and/or artificially created meaning. Moreover, the inclusion of items used in the ISR task in the EEG session would have provided clarity to the present results. These issues will be considered in Chapters 3 and 4.

Dyslexic participants were expected to show a relatively greater impact of semantic representations on vSTM and reading based on the primary systems hypothesis (Patterson et al., 2006; Patterson & Lambon Ralph, 1999; Ueno et al., 2011), and results of previous studies (Crisp et al., 2011; Crisp & Lambon Ralph, 2006; Hennessey et al., 2012; Hoffman et al., 2015; Jefferies, Crisp, & Lambon Ralph, 2006; Katz & Goodglass, 1990; Savill et al., 2019; Verhaegen et al., 2013). However, since no semantic effects were found overall it is difficult to confidently interpret that such a difference was not found in the present study in relation to group (i.e., dyslexic vs. non-dyslexic participants). Interestingly, dyslexic and non-dyslexic participants reached similar levels of performance at most tasks (except for phonological neighbour rejection accuracy in the phonological discrimination task, and reading accuracy in the speeded reading task, where non-dyslexic performance was better), despite apparent phonological difficulties as indicated by standardised psychometric measures. This seems to be in line with findings of a recent study in which non-dyslexic and dyslexic students learned picture-word associations and were tested on their learning with a matching task and a semantic task while continuous EEG was recorded (Rasamimanana et al., 2020). Rasamimanana et al. (2020) found that, despite a clear phonological deficit, students with a diagnosis of dyslexia reached similar performance than skilled readers at learning. They suggested that impaired readers need more frontal neural resources to complete the task, and benefit from semantic knowledge that was used to compensate their phonological deficit. It should be noted here that frequentist analysis was used in their study although hypotheses relied on unsignificant results between dyslexic and non-dyslexic adults. Bayesian analysis would have helped to clarify whether the absence of difference between the two groups was meaningful or not. Results of the phonological training task showed no between-group differences in the present study, with a Bayesian factor indicating moderate evidence in favour of the absence of a group effect for accuracy. This task resembled the matching task in Rasamimanana et al. (2020), whereby words were presented with a picture that matched or mismatched the previously learned unknown

Thai word-image association, but in which level of performance was lower for students with dyslexia than non-dyslexic students (a difference that was not found in the semantic task and was thus interpreted as reflecting a potential lack of statistical power). It could be that, in the present study, participants with dyslexia used semantic information to compensate their phonological difficulties (Cavalli, Duncan, et al., 2017; Schiff et al., 2019; van der Kleij et al., 2019) that otherwise, may have compromised the learning of new phonological forms. However, semantic compensation was not observed in the vSTM task, possibly because of the lack of establishment of semantic representations discussed above.

Conclusions

This study demonstrated that brief exposure to new phonological forms was sufficient to facilitate their recall in verbal short-term memory, which supports language-based accounts suggesting that vSTM draws on long term linguistic representations. Phonological familiarity also seemed to facilitate phonological processing at the neural level. Additional impact of semantic representations on lexical recall in ISR was not observable in participants irrespective of phonological skills, even though MMN responses in non-dyslexic participants indicated some perceptual differentiation related to training, possibly related to quality of form learning. The absence of a semantic effect in ISR could be due to unestablished representations in long term memory, providing insufficient support to produce an observable boost to vSTM performance, or to poor learning of the nonword-semantics associations. Thus, a consolidation period may be necessary to transfer episodic representations to semantic lexical representations as suggested by the complementary learning systems account (Davis & Gaskell, 2009), which could allow for semantic effects to emerge in vSTM. Moreover, the discussed concerns about learning levels will be addressed in the following chapters (Chapter 3 and 4) by methodological changes such as reducing the number of to-be-learn nonwords or associating nonwords to English words that benefit from already established long-term representations. If null semantic effects persist, even after refining the learning process, this could suggest that the newly formed semantic associations are perhaps too superficial or weakly connected to confer a substantial quantitative enhancement in vSTM. However, such an interpretation should nevertheless be treated cautiously: The absence of an effect in our study, as well as in some previous studies, does not conclusively rule out the influence of semantic associations. It could be the case that the specific conditions or methods employed were not optimal for observing this effect. Therefore, the importance of continuing to refine and enhance learning methods is crucial in the ongoing exploration of vSTM and its potential semantic reliance.

Chapter 3.

Influence of semantic associations on novel words in verbal short-term memory: Online experiment with dyslexic and non-dyslexic adults.

Open Science Framework link: https://osf.io/23kn5/

3.1 . Abstract

In this study, the contribution of newly acquired semantic associations to vSTM in dyslexic and non-dyslexic adults was re-examined. Methodological concerns raised in the previous chapter were addressed to improve the learning of nonwords and their associated semantic features. A reduced set of nonwords trained with or without semantic associations was used in an immediate serial task. Similar to Chapter 2, a recall advantage was found for phonologically familiarised, compared to untrained, nonwords and, unlike the previous study, a further advantage was observed for semantically trained nonwords over phonologically familiarised nonwords. The advantage for semantically trained nonwords was observed at the item level and did not affect phoneme migrations. In addition, dyslexic and non-dyslexic participants reached comparable performance across tasks and seemed to benefit from semantic associations at a similar level. These results suggest that long-term linguistic knowledge supports vSTM, in line with language-based models, but also with redintegrative processes taking place at the point of recall.

3.2 Introduction

Hearing a nonword just a few times helps us to recall it in vSTM (Majerus et al., 2004; Savill et al., 2015, 2017), and this was clearly observed in the previous study (Chapter 2 where phonological exposure to nonwords increased their likelihood of being recalled in ISR), and to a similar extent in both non-dyslexic and dyslexic participants. Such results demonstrate that long-term stored phonological knowledge supports the phonological trace at the item level in vSTM, which can be accounted by models of STM that propose distinct vSTM and LTM stores, whereby the decayed verbal short-term memory trace would be compared to long-term stored phonological representations at the point of recall to be reconstructed (Hulme et al., 1991; R. C. Martin et al., 1999; Nairne, 1990). Models assuming that vSTM reflects temporary activation of the language system in LTM can also explain these results since the temporary maintenance of the phonological trace will be directly affected by long-term stored linguistic representations (Acheson, Hamidi, et al., 2011; Cowan, 1999; N. Martin & Saffran, 1992; Nairne, 1990; Ruchkin et al., 2003). For instance, when nonwords were phonologically familiarised and paired with or without concrete referent images (i.e., either blurred or clear images of uncommon objects) during a short familiarisation task, they showed a recall advantage in immediate serial recall (ISR) over entirely new nonwords (Savill et al., 2015). This recall advantage was found both at the item and phoneme levels. Phonologically familiarised nonwords were more often accurately recalled, and their phonemes were less prone to separate and merge with other items of the list, suggesting that the phonological system constrains the phonological trace in vSTM. Phoneme-level results are best accounted for by language-based models (Acheson & MacDonald, 2009b; Majerus, 2013; N. Martin & Saffran, 1992; Patterson et al., 1994; Schwering & MacDonald, 2020), and particularly by the semantic binding hypothesis (Patterson et al., 1994) according to which the phonological system learns and stores the phonological sequence of an item when exposed to it, thus the more familiar an item is, the less likely it is for its constituent phonemes to break apart. In the context of Chapter 2 and Savill et al. (2015) experiments, phonologically familiarised nonwords benefited from phonological representations in the language systems, making them more stable than entirely new nonwords.

There was no additional contribution of novel semantic representations beyond phonological familiarity in Chapter 2. By contrast, Savill et al. (2017) observed a recall advantage for nonwords previously associated with semantic information over nonwords that were phonologically familiar only, suggesting that newly acquired semantic representations contribute to vSTM. Potential interpretations for the lack of effect found in Chapter 2 were explored in the previous discussion. One was that new semantic representations may require overnight consolidation to be established in long-term memory, as suggested by the complementary system account of word learning (Davis & Gaskell, 2009). However, no effect of consolidation was found in Savill et al. (2017), suggesting rapid acquisition of novel linguistic representations can lead to an effect of semantic knowledge in vSTM on the day of training. Alternatively, short training of the extended set of stimuli used in the previous study may have compromised learning of lexical-semantic associations. Namely, if the demand for resources exceeds the capacity of phonological memory (Baddeley, 1986), the processing and storage of language may suffer from degradation. Phonological memory plays an important part in phonological form learning (Gathercole & Baddeley, 1993), particularly when phonological sequences are uncommon, which can impede lexical and semantic processing (Papagno et al., 1991; Service, 1992; Storkel, 2001). In Chapter 2, phonological forms obeyed English phonology but did not have phonological neighbours, thus, phonological forms did not match existing phonological, lexical, and sematic representations. This allowed for all trained items to have the exact same level of representation and familiarity associated with them. However, due to their lack of links with established representations and the large number of items trained, more resources may have been dedicated to phonological processing, potentially exceeding the available resources, and consequently hamstringing the establishment of lexical-semantic representations. Therefore, a key aim for the design of the present study is to reinforce the learning of the nonword-image-description associations before assessing their recall in ISR alongside nonwords associated with blurred referents and untrained nonwords, in order to re-examine the role of phonological-lexical and semantic representations in vSTM in non-dyslexic and dyslexic individuals.

For this purpose, one of the changes was the addition of a repetition task to the training phase in the present study. A relationship between nonword repetition and vocabulary acquisition has been observed in children (Avons et al., 1998; Gathercole et al., 1997, 2005; Gathercole & Baddeley, 1989; Gathercole & Masoura, 2005; Michas & Henry, 1994; Service, 1992; Service & Kohonen, 1995) and adults (Atkins & Baddeley, 1998; Gupta, 2003). More precisely, since novel word learning rely on temporary storage of phonological representations as well as its quality (Gathercole, 2006), repeating a sequence of phonemes (e.g., a nonword) is thought to facilitate its representation in long-term memory. Novel word learning studies commonly use oral repetition within their training tasks (e.g., Henderson et al., 2013; Weighall et al., 2017). This encouraged its implementation in the current study to aid phonological learning in the context of its referent, which was hoped to improve phonological familiarity, as well as strengthening semantic-phonological links.

Furthermore, to reduce the resources demand on phonological memory and to ensure satisfactory levels of learning by the end of the training tasks, the set of trained nonwords was reduced to 24 items (compared to 72 nonwords in Chapter 2), and a learning criterion was added to the phonological training task whereby participants were required to reach at least 70% accuracy towards the end of the task (i.e., mean accuracy over the final 3 presentations of the nonwords and their associated image) to optimise the training effect.

Another important modification to the present study was that it was conducted online, due to the emergence of the global COVID-19 pandemic prohibiting continued face-to-face lab-based research. It was conducted using Gorilla (www.gorilla.sc), a reliable online experiment builder (Anwyl-Irvine et al., 2020), which allowed for the recruitment of bigger and wider samples of participants. The choice of Gorilla capitalised on a new beta functionality which allowed audio recording for individual trials enabling ISR transcriptions. Data from web-based remote experiments measuring cognitive abilities such as working memory seem to yield comparable results to those from lab-based environments (Ruiz et al., 2019; Segen et al., 2021), suggesting that online testing is a valid method in the context of the present experiment.

Assuming these modifications would support phonological learning as hoped, a recall advantage for phonologically familiarised items over new untrained nonwords in vSTM was predicted, replicating findings of Chapter 2. Second, if the reduction of trained nonwords, repetition, and learning criterion succeeded in making training more manageable and helping the improvement of the association between nonwords and their trained semantic features, there could be notable effects. Specifically, an additional effect of semantic associations might manifest as better recall in ISR for semantically trained nonword lists compared to phonologically familiarised nonword lists, both at the item and phoneme levels. Alternatively, if semantic representations do not further impact vSTM, recall performance would be comparable between semantically trained and phonologically familiarised nonword lists. Third, according to the primary systems hypothesis (Patterson & Lambon Ralph, 1999; Ueno et al., 2011), dyslexic participants were expected to show stronger effects of semantic training compared to non-dyslexic individuals.

3.3 Method

Participants

Sixty-two participants took part in this study; however, two participants were rejected from this experiment due to technical issues, hence data from sixty participants (39 females and 21 males) aged between 18 and 44 years (M = 27.92, SD = 7.03) were analysed. Participants with normal or normal-to-corrected vision and hearing were recruited via Prolific and SONA systems. Twenty-nine of the participants had no language or learning difficulties (mean age 28.14 years, SD = 7.47, 18 females) and 31 had a diagnosis of dyslexia (mean age 27.71 years, SD = 6.7, 21 females). Participants received payment for their participation (£7/hour) and gave their informed consent prior to the start of the study. Ethical approval was received from the Psychology Department Ethics Committee at York St John University.

Psychometric measures

Psychometric measures that can be used or adapted for use in an online environment were used to assess the profile of the participant groups recruited online. Phonological awareness was assessed with the Spoonerism test from the York Adult Assessment Battery-Revised (Warmington et al., 2013; used in previous chapter). Semantic knowledge was assessed via an electronic version of Warrington's Graded Synonyms (Warrington et al., 1998; used in previous chapter). Reading skills were assessed with the Rapid Online Assessment of Reading (ROAR) browser based lexical decision task (Yeatman et al., 2021), in which participants determine whether an item presented on screen is a word or a nonword by pressing a key accordingly as quickly and accurately as possible. There are 126 words and 126 nonwords presented in a randomised order in the ROAR task. The replacement of the published standardised reading measures, such as the Wide Range Achievement Test (WRAT) and the Test of Word Reading Efficiency (TOWRE) used in Chapter 2, with the Rapid Online Assessment of Reading (ROAR) browser-based lexical decision task was primarily due to our inability to use these established measures online (re: restrictions on public use of licensed tests).

Research conducted by Yeatman et al., (2020, 2021) supports the validity and reliability of ROAR as an effective tool for assessing reading abilities, which assures its comparability to traditional measures like WRAT and TOWRE. The Digit Span Task (adapted by Dean from Turner & Ridsdale, 2001) was used to assess short-term and working memory. This task is publicly available on Gorilla.sc, and is similar in design and function to the Digit Span subtest of the Wechsler Adult Intelligence Scale (WAIS). Finally, non-verbal reasoning was assessed with the Matrix Reasoning Item Bank (MaRs-IB, Chierchia et al., 2019). This open access computerised abstract reasoning test consists of incomplete 3 x 3 matrix with abstract shapes presented to the participants. One cell of the matrix is empty, and participants attempt to complete the matrix by selecting the missing shape amongst four possible alternatives.

Bayesian Independent t-tests were computed to compare cognitive profiles of the dyslexic and non-dyslexic groups (see **Table 3.1**). Poorer performance at measures of phonological abilities, short-term memory, and nonwords reading accuracy (spoonerisms task, digit span forward, and ROAR nonword) was observed for the dyslexic group compared to the non-dyslexic group. Groups did not differ on measures of working memory (digit span backwards), non-verbal reasoning, and semantic knowledge.

Table 3.1. *Psychometric measures for participants with and without dyslexia.*

		Dyslexics (n = 29)		Non-dyslexics (n=31)		Bayes factors
Measure		Mean	SD	Mean	SD	BF_{10}
Phonological awareness	**Spoonerisms**[a]	8.26	3.01	10.62	1.8	102
Reading	**ROAR**					
	RT-Words	338.35	114.95	283.8	84.88	0.1
	RT-Nonwords	460.38	197.63	360.35	97.32	0.09
	ACC-Words[b]	0.97	0.03	0.97	0.03	0.04
	ACC-Nonwords[b]	0.76	0.16	0.86	0.11	10.7
Working memory	**Digit Span**[c]					
	Forward	9.36	2.5	11.07	3.25	4.52
	Backward	7.1	2.98	8.38	2.23	2.16
Non-verbal reasoning	**MaRs-IB**[b]					
	ACC	0.51	0.18	0.56	0.17	0.1
Semantic knowledge	**Warrington's graded synonyms**[d]					
	ACC	32.74	6.83	34.55	5.71	0.44

Note. ACC = Accuracy, RT = Response Time (msec), SD = Standard Deviation. Bayes Factors (BF_{10}) > 3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect.

[a] *Maximum score = 12*

[b] *Mean accuracy*

[c] *Maximum score forward = 18, and backward = 16*

[d] *Maximum score = 50*

Stimuli

The stimuli used in this chapter was a subset of the nonwords used in Chapter 2 (see Appendix C for the full list of nonwords). Sixteen disyllabic nonwords with CVCVC structure and 8 monosyllabic (CVC) nonwords were grouped into three sets of eight disyllabic and four monosyllabic nonwords, to be allocated to the semantically trained (SEM), the phonologically familiarised (FAM), and the untrained (NEW) conditions. Identical to Chapter 2, in the SEM condition, nonwords were associated with colour images of unusual objects and three descriptions of the context of usage of the object, its mechanism, and its function. The objects chosen had no clear name, and their meaning was plausible with features identifiable in the photographs. The 12 images used in the training task were a selected subset of the ones used in Chapter 2. Twelve blurred versions of object pictures were assigned to the FAM condition. This way, semantically trained nonwords were associated with semantic features (i.e., an image and written descriptions), whereas nonwords associated with blurred images were only phonologically familiarised.

For the immediate serial recall task, 18 lists of four nonwords were created for each condition (SEM, FAM and NEW). These lists did not contain repetition of phonemes so that phoneme migrations could be tracked at recall. A list of stimuli is provided in the Appendices. Finally, a 2.5 cm diameter image of a blue dot sourced from the internet was for use in the online version of the ISR task (see Appendix C for an example of an ISR 'blue dot trial'). This was used in dummy trials, which were intended to discourage participants from cheating and act as an attention check (see procedure subsection for more information about these trials).

Procedure

Gorilla Experiment Builder (www.gorilla.sc) was used to design and host the present experiment. Online testing does not allow for the same control over the environment as laboratory-based experiments: the remote aspect of web-based experiments means that instructions cannot be enforced, and participants may be distracted, multitasking, or cheating whilst completing tasks (Kochari, 2019; Sauter et al., 2020). In an attempt to overcome these issues, specific features were added to this experiment such as a performance criterion for the training task and attention checks, following Sauter et al. (2020) recommendations (see below for further details).

Training tasks

Similar to Chapter 2, the training phase of this experiment consisted of two tasks. The first task (i.e., semantic training task) was identical to Chapter 2, whereby participants learnt the associations between images of uncommon objects and their descriptions for the semantically trained condition, and were also exposed to blurred images for the phonologically familiarised condition. Each image was presented nine times in total, in a pseudo-random order. The only difference from Chapter 2 was that a total of 24 images (12 in each condition) were used in the present experiment (instead of 72 in Chapter 2).

In the following phonological training task, previously trained images were associated with auditory nonwords. In the first phase of this task, 24 images (12 clear from the SEM condition and 12 blurred from the FAM condition of the previous semantic training task) were presented simultaneously with their associated auditory nonwords (see **Figure 3.1**). As before, in each trial, an image was displayed on the screen, accompanied by the playback of its associated auditory nonword. This time, participants were instructed to repeat the nonword and to memorise the image-nonword associations. After completing these steps, they were directed to click on a 'next' button located at the bottom right of the screen. The learning of these image-nonword associations was subsequently assessed in the second phase (see **Figure 3.1**). This phase followed the same testing procedure as detailed in the experiment described in Chapter 2. Three versions of this task were created with different sets of nonwords being associated with the SEM and FAM conditions, and were rotated across participants (three versions were to fully rotate conditions between the three sets of stimuli tested in ISR).

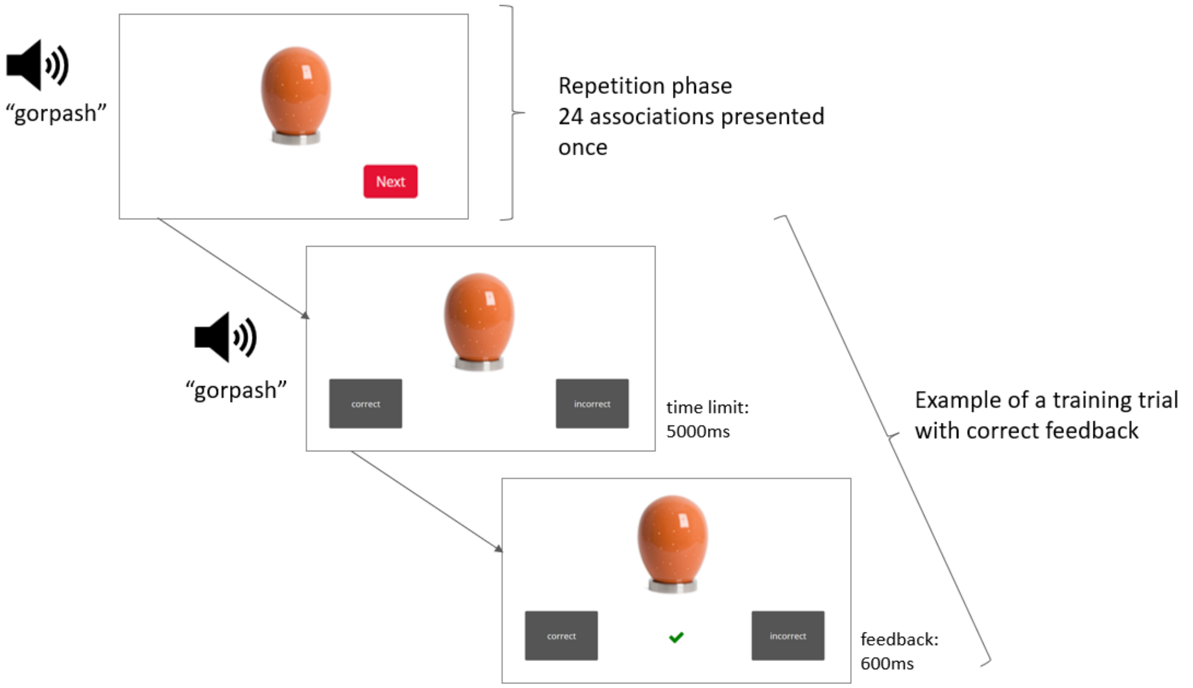


Figure 3.1. *Example of one trial of the repetition phase of the training task, followed by one example trial of the second phase of the training task with correct feedback.*

Learning throughout the two training tasks was assessed by improvements in accuracy and reaction times. To ensure that participants learnt the association to a reasonable degree, a minimum of 70% accuracy in the last third trials of the phonological training task was necessary. If participants did not reach this accuracy level, they were rejected from the study. Better accuracy and shorter reaction times were expected over the course of the training tasks as a result of learning.

Free recall task

Like Chapter 2, to measure the availability of the phonological forms of trained nonwords, participants had two minutes to orally produce as many nonwords as they could remember from the training tasks. Responses were digitally recorded and phonologically transcribed to examine whether the availability of lexical and semantic representations benefit their phonological retrieval.

Immediate serial recall task

In the ISR task participants were asked to recall lists of four auditory nonwords back in order. There were 54 trials made exclusively of semantically trained, phonologically familiar, and new untrained items presented in a fixed pseudo-random order, which resulted in 18 trials per condition. Nonwords were presented at a rate of 1.25s while an exclamation mark appeared on screen, following which a question mark prompted participants to recall the nonwords back in order. Participants were given a maximum time limit of 10 seconds to repeat the lists. There were three versions of this task with different list orders to allow for counterbalancing.

In order to discourage cheating and to keep participants motivated in the absence of lab-based conditions, a parallel task was embedded in the immediate serial task. For this task, participants were rarely presented with an image of a blue dot (4 times over the course of the task) and were asked to click on the dot when they saw it appearing (see Appendix D for an example of a ‘blue dot trial’). This task was intended to encourage participants to keep their hands on the mouse and keyboard and stay focused on the screen, which was intended to discourage writing the nonwords during the encoding phases of the task. Four dummy trials comprising a blue dot were added to the original 54 ISR trials and were not included in the analyses. These trials contained four nonwords that were used in Chapter 2 and were not part of the SEM, FAM and NEW conditions of the present experiment.

Picture naming task

A picture naming task was used in this experiment to assess the acquisition of the phonological forms and their independent production. In this task, all images from the SEM and FAM training conditions were shown to the participants one after the other. Participants were asked to attempt to generate their corresponding names, or to say “pass” if they could not remember them, and to click on a ‘next’ button on screen to start the next trial. This task provided an index of the specification of the phonological representations in the mental lexicon, and of their association to a visual referent.

Additional online testing and attention checks

After participants filled the consent form, a simple attention check determined whether they were reading instructions thoroughly. Participants were asked to press a specific key instead of clicking on the ‘next’ button to continue the experiment (see Appendix H). If participants failed this task, they were automatically rejected from the experiment. In addition, after the experiment’s debrief, a series of questions were asked to the participants, which aimed to monitor the environment in which they completed the experiment, and potential distractions that occurred over the course of the experiment. For example, participants were asked: “Were you doing something else at any point of the experiment? (e.g., checking your phone, having a conversation with someone, watching TV)”, or “Did you cheat during the experiment? (e.g., writing down the words you had to recall). You will still be paid if you answer "yes", so please be honest, it is particularly important for the scientific quality of this research.”

3.4 Immediate serial recall coding

The transcription procedure followed the one used in Chapter 2 (and in Savill et al., 2017). Responses were manually transcribed phoneme-by-phoneme, and the coding scheme examined the effect of phonological and semantic training on recall and phonological stability. Item level responses were categorised as correctly recalled in any serial position (CAP), which comprises items recalled in the correct position (CIP) and items recalled in the incorrect serial position (ORD). Phonemes that were recalled in an incorrect order but retained their position within the syllable, as compared to the target, were classified as phoneme migrationsStatistical analyses

Identical to Chapter 2, Bayesian analyses were computed and BF_{10} was used to assess the evidence's strength in favor of the alternative model (H_1) compared to the null model (H_0). $BF_{10} < 1$ provides no evidence in favour of H_1, BF_{10} between 1 and 3 provides weak evidence in favour of H_1, BF_{10} between 3 and 10 provides substantial evidence in favour of H_1, BF_{10} between 10 and 30 provides strong evidence in favour of H_1, BF_{10} between 30 and 100 provides very strong evidence in favour of H_1, and $BF_{10}> 100$ provides decisive evidence in favour of H_1 (Lee & Wagenmakers, 2014). All analyses were performed using the default wide Cauchy prior distribution of $r = \sqrt{2}/2$.

Statistical analyses were conducted using JASP (2020). Unless stated otherwise, Bayesian mixed ANOVAs were computed with the data from each task, with group (dyslexic vs. non-dyslexic participants) as a between-subject factor and condition (SEM vs. FAM vs. NEW) as within-subject factor.

For the immediate serial recall task several analyses were performed: item level responses were first examined, CAP, CIP and ORD measures were analysed as a function of group (non-dyslexic vs. dyslexic participants), and item condition (i.e., FAM vs. NEW, and FAM vs. SEM). Subsequently, the impact of training was independently evaluated for both the dyslexic and non-dyslexic groups using Bayesian t-tests. Phoneme migrations were then analysed following the same principle.

Finally, the relationship between phonological skills (determined by the averaged spoonerisms and ROAR nonword accuracy z scores) and training effects were examined, similar to Savill et al. (2019). Correlations between the effect of phonological familiarisation (the ratio between phonologically familiarised and new item CAP recall) and phonological skills, as well as between semantic effects (the ratio between semantically trained and phonologically familiarised item CAP recall) and phonological skills, were computed.

3.5 Results

Semantic training

Enhancements in accuracy and response time for correct trials during the semantic training verified that both non-dyslexic and dyslexic participants effectively grasped the links between the images and their definitions (see **Figure 3.2**). Bayesian mixed ANOVA revealed that the accuracy data were best represented by the model that included only the main effect of the image trial, $BF_{10} = 9.32*10^{48}$, indicating decisive evidence in favour of an effect of trial number. There was no group difference in accuracy ($BF_{10} = 0.24$), and no interaction between trial number and group ($BF_{10} = 0.22$). There was decisive evidence in favour of an effect of trial number on reaction time ($BF_{10} = 2.52*10^{114}$). Reaction times were faster in the non-dyslexic group than in the dyslexic group ($BF_{10} = 4.02$).

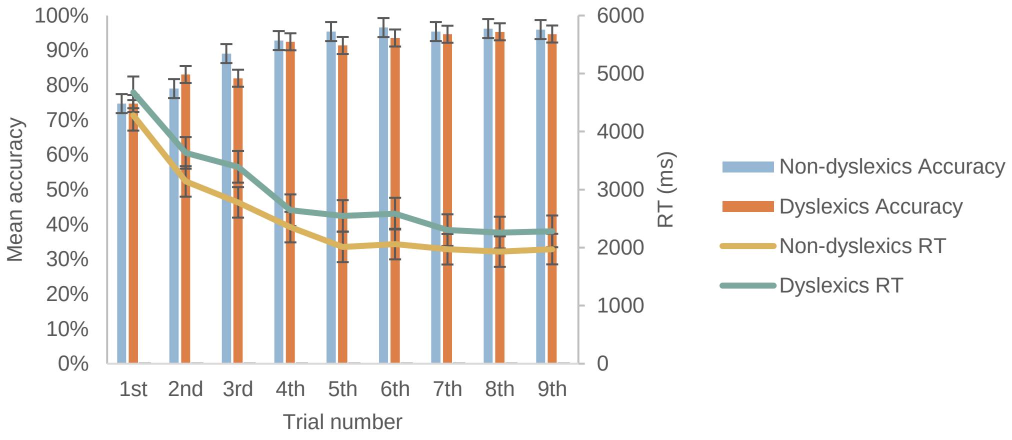


Figure 3.2. *Improvement in accuracy and reaction time during the semantic training observed in both dyslexic and non-dyslexic groups. Error bars represent +/- 1 SE.*

Phonological familiarisation training task

The improvement of reaction time and accuracy indicated that, by the end of the training task, participants had mastered the associations between images and nonwords (main effect of trial number on accuracy: $BF_{10} = 2.52*10^{153}$; and on RT: $BF_{10} = 5.83*10^{49}$, see **Figure 3.3**). The image type (clear for the SEM condition and blurred for the FAM condition) impacted accuracy performance on this task, ($BF_{10} = 2.56*10^{19}$), with SEM image-nonword associations being easier to learn than the FAM blurred image-nonword associations but reaction time was not impacted by the image type (BF_{10} = 0.2). There were no significant differences between the groups for reaction times (BF_{10} = 0.41) and accuracy (BF_{10} = 0.26), and no interaction (BF_{10} = 0.18), suggesting that both groups learnt the associations to a similar level.

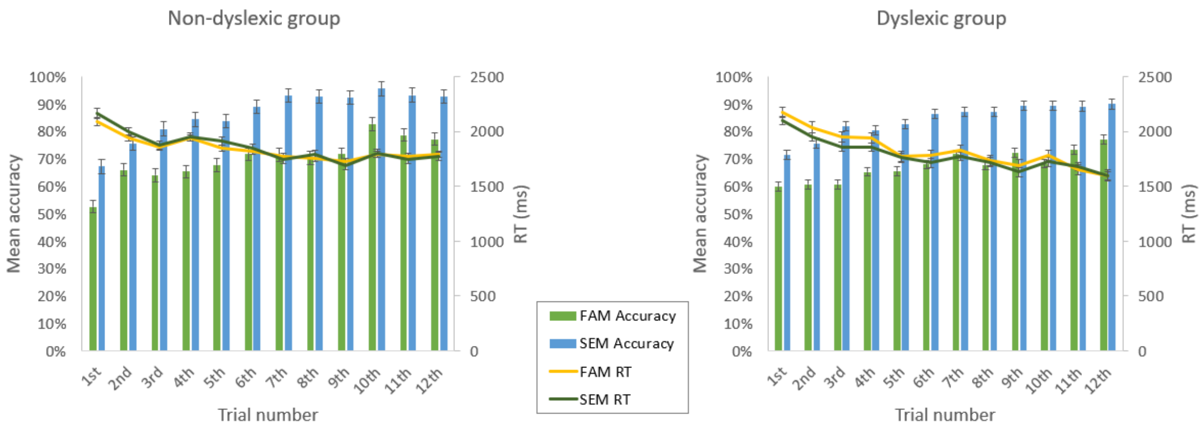


Figure 3.3. *Improvement in pairing accuracy and reaction time in the non-dyslexic group (left graph) and the dyslexic group (right graph) during the phonological familiarisation task. SEM pairings correspond to the association of a nonword with its image representation (an unfamiliar object), and FAM pairings correspond to the association of a nonword with a blurred image.*

Free Recall

Participants recalled few of the trained nonwords. When participants generated more than one item, they tended come from the SEM training condition (main effect of training condition BF_{10} = 5506.92, see **Table 3.2**). There were no group differences (BF_{10} = 0.22) and no significant interactions (BF_{incl} = 0.21).

Table 3.2. *Descriptive statistics for the free recall task. Average number of nonwords recalled (out of 12 per condition).*

Training condition	Group	Mean	SD
SEM	Non-dyslexic	3.07	3.11
	Dyslexic	2.93	2.07
FAM	Non-dyslexic	1.54	1.50
	Dyslexic	1.57	1.07

Note. SD = Standard Deviation

Picture naming task

On average participants generated 27.56% (*SD* = 17.23%) of the correct object's name. These names were more likely to be produced from the clear (SEM) than from the blurred image (FAM) conditions (see **Table 3.3**, $BF_{10} = 6.8*10^{12}$). There was no between-group difference ($BF_{10} = 0.31$), and no interaction between group and training condition ($BF_{10} = 0.32$).

Table 3.3*. Descriptive statistics for the picture naming task showing the average of correctly named pictures (out of 12).*

Training condition	Group	Mean	SD
SEM	Non-dyslexic	5.30	3.06
	Dyslexic	4.71	2.87
FAM	Non-dyslexic	1.85	1.98
	Dyslexic	1.42	1.31

Immediate Serial Recall

Nonword recall performance

Bayesian independent samples t-tests were computed to compare dyslexic and non-dyslexic participants recall accuracy for NEW untrained nonwords. Descriptives statistics show that non-dyslexic participants recalled more NEW nonwords in the correct position compared to dyslexic participants (see **Figure 3.4**), this difference was supported by weak evidence ($BF_{10} = 2.15$).

Phonological familiarisation

The number of items recalled in *any* position (CAP) was impacted by phonological familiarisation ($BF_{10} = 76857$). More phonologically familiarised (FAM) items were recalled in any position compared to (NEW) untrained items (see **Figure 3.4**). Recall performance was similar between groups ($BF_{10} = 1.06$), and there was no interaction between training condition and group ($BF_{10} = 0.88$).

Within the items recalled, the effect of training was found to be limited to items recalled within the correct position ($BF_{10} = 2903$, see **Figure 3.4**); items in the incorrect position were marginally impacted on the other hand (BF_{10} = 1.54). Group performance did not significantly differ for these two measures (item CIP: BF_{10} = 1.94; item ORD: BF_{10} = 0.74). There were no interactions between CIP and group (BF_{10} = 0.76) and between ORD and group (BF_{10} = 1.76).

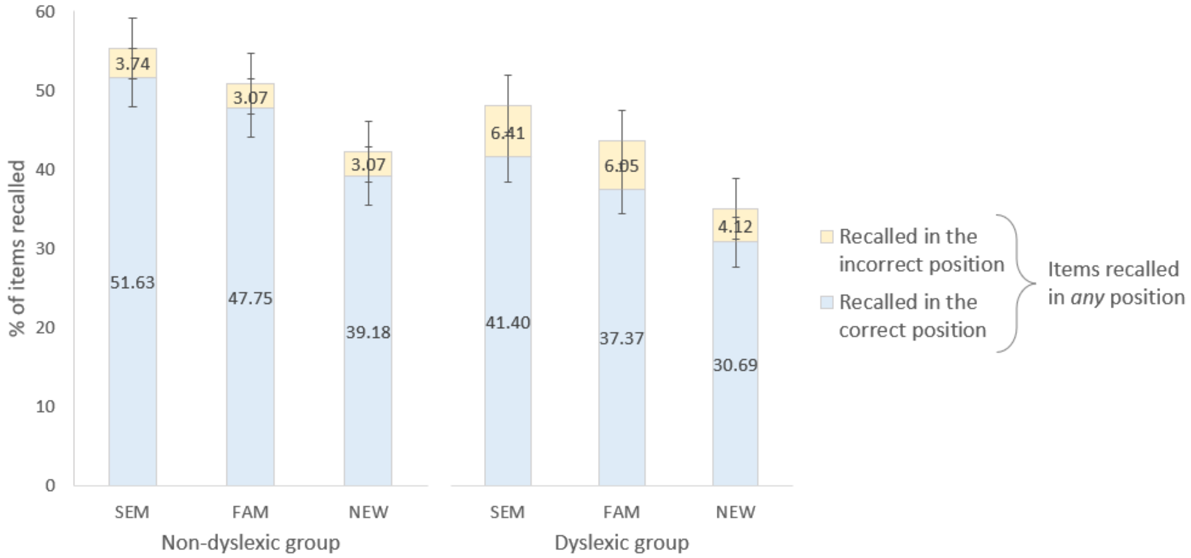


Figure 3.4*. Percentage of items recalled in the correct and incorrect serial position, forming the CAP (items recalled in any position) measure. Non-dyslexic participants are depicted on the left graph and dyslexic participants on the right graph. SEM = semantically trained items, FAM = phonologically familiarised items, NEW = new untrained items.*

Individual analyses of CAP recall performance for both dyslexic and non-dyslexic participants revealed a shared benefit from phonological training in terms of items correctly recalled in any position (CAP), with notably very strong evidence for this effect in both the dyslexic group (BF_{10} = 396.38) and non-dyslexic group (BF_{10} = 47.12). Likewise, the impact of phonological familiarisation was observed in the correct serial position (CIP) recall performance, with significant evidence seen for the dyslexic group (BF_{10} = 19.97) and non-dyslexic group (BF_{10} = 30.74). However, a divergence emerged in relation to order errors, which were influenced by training exclusively in the dyslexic group (BF_{10} = 3.09), while the non-dyslexic group did not exhibit any such training effect (BF_{10} = 0.2).

Analyses at the phoneme level indicated that phonological familiarisation exerted a discernible influence on phoneme migrations. Phonemes from familiarised items were found to be less susceptible to migrate compared to those from novel, untrained items

(BF_{10} = 3.14, refer to **Table 3.4**). The propensity for phoneme migrations remained consistent across the dyslexic and non-dyslexic groups (BF_{10} = 0.86), with no observable interactions between phoneme migrations and group status (BF_{10} = 0.7). When each group was separately analysed, it emerged that phonological familiarisation influenced phoneme migrations solely in the non-dyslexic group (BF_{10} = 17.68). Meanwhile, the dyslexic group did not display any significant evidence of this effect (BF_{10} = 0.27).

Table 3.4 *Mean percentages of phoneme migrations across different training conditions.*

	SEM	FAM	NEW
All participants	11.1 (10.04)	11.29 (9.05)	13.86 (9.33)
Non-dyslexic group	8.69 (7.73)	8.89 (7.79)	12.97 (9.04)
Dyslexic group	13.35 (11.47)	13.54 (9.68)	14.69 (9.68)

Note. Standard Deviations in parentheses.

Semantic associations

Semantic associations exerted a further influence on recall, leading to a greater number of items being remembered in any position for nonwords trained under the semantically associated condition compared to the phonologically familiarised-only condition (BF_{10} = 6.02, see **Figure 3.4**). This recall benefit was observed at a similar level in the dyslexic and the non-dyslexic groups (main effect of group: BF_{10} = 0.97), and there was no interaction between training condition and group (BF_{incl} = 0.47).

The measure of "items recalled in any position" encompasses both items accurately recalled in their original sequence and those remembered out of order. Notably, items that were subject to semantic training were more frequently recalled in their correct serial order compared to items that had only undergone phonological familiarisation (BF_{10} = 3.83, see **Figure 3.4**). This recall benefit was marginally impacted by group (BF_{10} = 1.81), and group did not interact with training condition (BF_{incl} = 0.48). Items recalled in the incorrect position were not impacted by training condition (BF_{10} = 0.31), and dyslexic and non-dyslexic participants recalled a similar amount of nonwords out of sequence (BF_{10} = 0.70). There was no interaction (BF_{10} = 0.12).

When broken down into separate analyses for dyslexic and non-dyslexic groups, it was found that the enhanced CAP recall for semantically trained items was consistent across both groups, with a roughly equal effect size (BF_{10} = 1.12 in the dyslexic group, and

BF_{10} = 1.1 in the non-dyslexic group). When examining items recalled in their correct position, the dyslexic group showed only marginal evidence of a benefit from semantic training (BF_{10} = 1.04), and no such effect was observed in the non-dyslexic group (BF 10 = 0.77). Regarding order errors, semantic training did not influence their occurrence in either the dyslexic (BF_{10} = 0.22) or non-dyslexic group (BF_{10} = 0.29).

At the phoneme level, semantic associations did not impact phoneme migrations (BF_{10} = 0.24, see **Table 3.4**), suggesting that phonemes from target phonologically familiarised and semantically trained nonwords were equally likely to be produced in the wrong position. There was weak evidence in favour of a group difference in the production of phoneme migrations, where dyslexic participants produced slightly more phoneme migrations than non-dyslexic participants (BF_{10} = 1.71). There was no interaction between training condition and group (BF_{incl} = 0.10).

When the impact of semantic training on phoneme migrations was independently analysed for both the dyslexic and non-dyslexic groups, it was found that neither group showed a significant effect. This was evidenced by a Bayesian factor of 0.19 for the dyslexic group and 0.2 for the non-dyslexic group, indicating evidence in favour of the null hypothesis.

Relationship with phonological skills

The relationship between phonological skills (indexed by standardised performance at psychometric tasks) and the magnitude of the phonological familiarisation effect was examined. It showed that stronger effects of phonological familiarisation were weakly associated with better phonological skills (r = 0.26, BF_{10} = 1.16, p = .04, see **Figure 3.5** left panel). There was not enough evidence in favour of a relationship between phonological skill and the semantic effect (r = -0.12, BF_{10} = 0.24, p = .38, see **Figure 3.5** right panel).

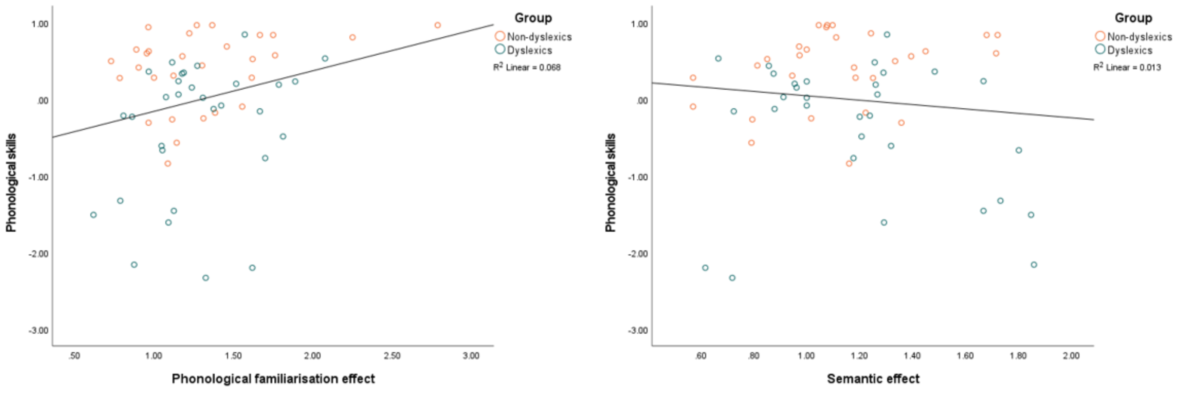


Figure 3.5. *Left panel: positive correlation between phonological skills and the phonological familiarisation effect. Right panel: Negative corelation between phonological skills and the effect of semantic training in items recalled in any position at the ISR task.*

3.6 Discussion

The present study re-examined whether phonological familiarity with nonwords and their semantic associations impacted recall in vSTM, and compared recall performance of dyslexic and non-dyslexic participants to determine the relationship between semantic support and phonological abilities. This experiment followed the design used in Chapter 2 with some key adjustments such as fewer nonwords trained (i.e., 24 versus 72 in Chapter 2), verbal repetition during phonological training and the addition of a learning criterion. It was predicted that measures of verbal short-term memory would demonstrate a recall advantage for phonologically familiarised, over new untrained, nonwords, and that an additional benefit would be observed for semantically trained nonwords at the phoneme and item levels. This semantic effect may be amplified for participants with weaker phonological abilities (i.e., dyslexic participants).

As expected, phonologically familiarised items showed a substantial serial recall advantage over unfamiliar forms, similar to Chapter 2 ISR results. This advantage was observed at the item level (more phonologically familiarised nonwords recalled in any position, and in the correct serial position), and at the phoneme level with fewer phoneme migrations for phonologically familiarised nonwords compared to new nonwords. The influence of phonological and lexical knowledge on vSTM tasks have been demonstrated in a myriad of studies (Brener, 1940; Jefferies, Frankish, & Lambon Ralph, 2006b; Majerus et al., 2004; Majerus & Van der Linden, 2003; Savill et al., 2015, 2017). For example, incidental learning of an artificial phonotactic grammar with sublexical phonotactic rules of a continuous phonological sequence impacted later nonword repetition performance in Majerus et al. (2004), suggesting that long-term stored phonological representations and sublexical phonological knowledge support vSTM. Similarly, lexical effects (i.e., better recall performance for words over nonwords) have been found in vSTM even when controlling for articulation rate (Hulme et al., 1991), and for phonotactic probabilities (Gathercole, Service, et al., 1999). These findings, together with results of the present study, are in line with models of vSTM that posit intervention of long-term stored lexical phonological knowledge in vSTM maintenance and recall (Baddeley et al., 1998; Cowan, 1999; Hulme et al., 1991; N. Martin & Saffran, 1992; R. C. Martin et al., 1999; Nairne, 1990; Ruchkin et al., 2003). They could alternatively be interpreted through the levels of processing framework (Craik & Lockhart, 1972), in which the depth of processing impacts how well we remember something. In this case, phonologically familiar items, which undergo deeper processing, are recalled better than unfamiliar ones.

The differential impact of phonological familiarisation on phoneme migrations between the non-dyslexic and dyslexic groups offers an interesting discussion point. For the non-dyslexic group, phonological familiarisation significantly reduced phoneme migrations, suggestive of a beneficial effect of familiarisation on phoneme-level accuracy during recall. However, for the dyslexic group, no significant effect was observed. One possibility to explain these differing effects may be that the dyslexic group might be focusing more on the order of the larger units, i.e., items. The potential trade-off between item-level ordering and phoneme-level precision in the dyslexic group might indicate differences in the underlying cognitive and neural mechanisms that support vSTM in dyslexia. That is, instead of focusing on the order of individual sounds within words, they might focus on the order of words within sentences or phrases. This shift to item-level ordering could serve as a compensatory mechanism that leverages lexical-semantic cues to support vSTM. However, it could simply reflect a subtle difference in the magnitude of the learning effect manifesting as differences between groups in the impact on errors in recall.

Unlike Chapter 2 results, a further impact of trained semantic associations was found on item recall in ISR, aligning with previous findings (Savill et al., 2017). The decrease of the number of trained nonwords and the addition of a repetition task in the training phase, in comparison to Chapter 2, is thus likely to have improved learning of the correct associations, as shown by the better ability to freely recall the nonwords after training (participants generated approximately twice as many nonwords). Spoken repetition is likely to have led to deeper encoding of information: by repeating the nonword-image associations, participants would have engaged in additional cognitive processing of these stimuli, strengthening their encoding into memory. This improved encoding can help increase the number of items that can be successfully retrieved later (Craik & Tulving, 1975).

Here, semantic associations increased the probability of recalling whole items correctly without impacting item order errors and phoneme migration errors. Previous vSTM studies found an impact of long-term stored representation on item identity errors but not on serial order maintenance, suggesting that order information may be independent from the linguistic system that maintains item identity (Campoy et al., 2015; Hulme et al., 1997, 2003; Romani et al., 2008; Saint-Aubin & Poirier, 2005; Walker & Hulme, 1999). Neuropsychological and neuroimaging studies indicate distinct mechanisms for the retention of item identity and serial order information (Attout et al., 2012; Guidali et al., 2019; Leavitt et al., 2017; Majerus et al., 2007; Martinez-Perez et al., 2013). A recent computational modelling approach confirmed this stance since a purely activation-based architecture - which predicts that order information retention takes place exclusively within the linguistic system through feed-forward activations of phonological and semantic representations, without the need for a separate system – failed to account for the interaction between semantic representations and serial order maintenance (Kowialiewski, Lemaire, et al., 2021). This assumption is in line with order results found in the present study, since semantic associations did not impact order errors, but differs from previous findings at the phoneme level (Jefferies, Frankish, & Lambon Ralph, 2006a, 2006b; Savill et al., 2017).

If semantic representations help to bind phonemes together from the encoding stage, as predicted by the semantic binding hypothesis (Patterson et al., 1994), then fewer phoneme migration errors could be expected for the semantically trained items compared to phonologically familiar nonwords. On the other hand, if a degraded phonological trace is reconstructed at the moment of recall as suggested by the redintegration accounts (Hulme et al., 1991), semantic factors should impact the probability of recalling whole items correctly without impacting phoneme migration errors. Since results demonstrated an absence of evidence for semantic influence on migration errors, this study only partially corroborates findings of Savill et al. (2017), whereby semantic representations stabilised the phonological trace in vSTM as shown by fewer migrations and intrusions errors for semantically trained items. Both the redintegration and the semantic binding frameworks can account for the present experiment's data, since meaning constrained recall at the item level, but no did not influence phoneme binding. However, in the original redintegration framework, the reconstruction of the memoranda is achieved at the lexical level, which does not account for semantic effects on recall observed in the current study (Hulme et al., 1997). Thus, language-based accounts can better predict our results at the whole item level, but semantic binding was not observed at the phoneme level.

The magnitude of the semantic association effect was comparable in dyslexic and non-dyslexic groups. According to the primary systems hypothesis, a stronger effect of trained semantic associations might have been observed at the ISR task in the dyslexic group. Such effects have been found empirically in participants with weak phonological skills (Jefferies et al., 2007; Jefferies, Crisp, & Lambon Ralph, 2006; Katz & Goodglass, 1990; Verhaegen et al., 2013; Wilshire & Fisher, 2004), and in reading tasks with dyslexic children (Hennessey et al., 2012). Present result suggest that dyslexic individuals benefit from semantic representations in vSTM, but that this benefit did not seem to be modulated by phonological abilities (as indexed by psychometric tasks, at least). Several interpretations can be put forward to explain this result.

First, it could be that despite relative phonological weaknesses, newly acquired semantic features does provide support, but the magnitude of the effect is too subtle to differentiate at a continuous level with statistical power. Weak evidence indicating poorer untrained nonword recall accuracy for non-dyslexic participants compared to dyslexic participants, hints that the absence of this difference in recalling trained nonwords might be due to dyslexic individuals drawing some advantage from lexical-semantic information, enabling them to achieve performance levels similar to those of non-dyslexic individuals. It should be noted here that measures of phonological abilities revealed some overlap between groups even though strong evidence was found in favour of a statistical difference of performance between groups. Hence, semantic compensatory mechanisms may not arise when support from the phonological system is sufficient, as suggested by previous studies showing that semantic support affects recall to a greater degree when phonological support is weak (Savill et al., 2019; see also Ueno et al., 2014). However, the analysis of the relationship between phonological abilities and the effect of semantic training in ISR did not significantly corroborate these findings. Interestingly, the effect of phonological familiarisation correlated with phonological abilities - although weakly - suggesting that participants with better phonological abilities benefited from phonological familiarisation to a greater extent than participants with weak phonological abilities. The observed correlation, albeit weak, is not surprising since participants with more robust phonological skills might better benefit from phonological familiarisation. This is likely due to their enhanced precision in learning phonological forms, which can positively impact their recall performance. These findings can be viewed in the context of the well-documented association between phonological skills and various language-related tasks, such as reading and spelling (Bradley & Bryant, 1983; Wagner & Torgesen, 1987). Specifically, individuals with stronger phonological abilities have been found to perform better on tasks requiring phonological manipulation, suggesting a more precise representation and processing of phonological information (Wagner et al., 1994).

Second, in the training tasks, dyslexic participants showed similar levels of accuracy to the non-dyslexic group for phonologically familiarised and semantically trained nonwords. Measures of independent production of the trained items (i.e., free recall and picture naming tasks) and immediate recall also indicated no difference between dyslexic and non-dyslexic participants, with a strong effect of semantic training. These findings are in line with a recent ERP study that analysed semantic compensation in students with dyslexia (Rasamimanana et al., 2020). Non-dyslexic and dyslexic students learnt picture-word associations and were tested on their learning with a matching task and a semantic task while continuous EEG was recorded. It seemed that, despite a clear phonological deficit, students with a diagnosis of dyslexia reached similar performance than skilled readers at learning, authors suggested that impaired readers need more frontal resources to complete the task, and benefited from semantic knowledge that is used to compensate their phonological deficit. Similarly, a few studies with dyslexic children have shown a shift towards the lexical-semantic system in reading words aloud (Cavalli et al., 2016; Elbro & Arnbak, 1996; Hennessey et al., 2012; Snowling, 1995; Snowling et al., 2000; Stanovich, 1980a, 1998; Vellutino et al., 2004a). In addition, neuroimaging data suggest that university students with a history of dyslexia rely on semantic representations to a greater extent than non-dyslexic students, indicated by early activation of frontal regions of university students in a primed lexical decision task (Cavalli, Colé, et al., 2017). The online nature of the present study did not allow for neuroimaging measures to be gathered; however, future studies should employ such techniques to assess neural recruitment during vSTM tasks in dyslexic participants to determine whether the lack of behavioural differences between the groups is the consequence of different neural recruitment (i.e., earlier and greater recruitment of the frontal regions), or evidence an absence of semantic compensation.

Semantic effects in vSTM after the learning of phonological forms and their associated meaning have been observed only a handful of times (Savill et al., 2017, and the present study). Considering other studies have argued that “meaning is useless” (Benetello et al., 2015; Papagno et al., 2013) when training unfamiliar words (i.e., Croatian words to Italian speakers in Benetello et al. 2015) with or without meaning associated to them, and the relatively small semantic effect found in studies that argue that “meaning is useful”, more evidence is needed to establish the role of semantic representations irrespective of phonological familiarity. That is, the superficial conception of semantic representations relied upon in Chapter 2 and 3, and their subsequent effects on vSTM may have been underpinned by episodic long-term memory traces which were not yet instantiated within semantic cortical networks. Thus, the observed effects in ISR were likely to have arisen from episodic perceptual associations, which may not be as relevant as semantic effects otherwise seen in vSTM in studies using existing words (e.g., Acheson et al., 2010; Campoy et al., 2015; L. M. Miller & Roodenrys, 2009; Romani et al., 2008; Walker & Hulme, 1999). However, using nonwords with trained associations is a means to examine semantic contribution to vSTM independently of phonological familiarity, ergo the next study of this thesis (Chapter 4) employed a similar stance to the present and previous studies (Savill et al., 2015, 2017) by training nonwords for subsequent use in ISR, but with a new paradigm, whereby nonwords were associated to real, familiar English words manipulated for their semantic properties. This ought to remove the artificial aspect of the trained semantic associations used in the present study by relying on well-established semantic representations that existing words enjoy. In addition, this new design would allow us to determine whether the impact of newly trained content depends on the type of semantic associations, since different content have yielded to different results (i.e., images in Savill et al. 2015, drawings in Benetello et al. 2015, and images with written definitions in Savill et al., 2017 and in the present study).

In sum, newly acquired phonological-lexical representations contribute to verbal short-term memory in dyslexic and language unimpaired individuals. A further impact of semantic associations was also observed in both groups on item recall accuracy in ISR, suggesting that long-term linguistic knowledge supports vSTM which is in line with language-based models, but also with redintegrative processes taking place at recall. This advantage for semantically trained nonwords was observed at a comparable level in dyslexic and non-dyslexic individuals, and phonological skills did not seem to correlate with the magnitude of the semantic association effect, suggesting that dyslexic adults did not rely on newly acquired semantic associations to a greater extent than non-dyslexic participants. However, the provision of lexical-semantic information may have helped dyslexic participants to achieve recall accuracy comparable to that of non-dyslexic individuals. Associating phonological forms to pre-existing semantic representations with varying semantic features might ensure that trained nonwords are linked with amodal representations in semantic memory rather than to more episodic perceptual representations, as suggested by the findings of the present study. The next study will thus employ this novel paradigm to examine the effect of semantic representations on vSTM in dyslexic and non-dyslexic adults.

Chapter 4.

Associating familiar word forms with nonwords: Contribution of word imageability to short-term memory for newly trained nonwords in dyslexic and non-dyslexic adults.

Open Science Framework link: https://osf.io/23kn5/

4.1 Abstract

The present study adopted a novel approach to examine the effect of long-term linguistic representations on verbal short-term memory, via word association. Namely, nonwords were associated with either high or low imageability words in a training phase, before being assessed in immediate serial recall lists alongside new untrained nonwords. The hope of this paradigm was for existing (lexical)-semantic representations of the words to be updated to include the associated nonword forms. The manipulation was predicated on the basis that, by the end of the training task, nonwords could benefit from established semantic networks with varying levels of features and richness by virtue of their indirect word association (i.e., with high imageability nonwords having richer semantic associations than low imageability words). A robust recall advantage was found for trained nonwords compared to new untrained nonwords both in dyslexic and in non-dyslexic groups, suggesting that phonological familiarity with newly acquired phonological forms improves vSTM span. However, there was no difference in recall performance between nonwords associated with high and low imageability words. This could be explained by various methodological limitations, such as the choice of high imageability words and their written presentation in the learning phase, or the lack of integration of these new forms in semantic networks related to the brief training paradigm.

4.2 Introduction

Considering the results from Chapter 2 and Chapter 3 studies, in which semantic contributions to vSTM were tested through learnt associations between nonwords and multidimensional novel object representations (which may not have necessarily produced new semantic representations to assess), the present study used a different training approach consisting of pairing nonwords with existing English words. Learning these pairings should thus result in the updating of semantic representation to include trained nonwords.

The effect of associating novel words with existing concepts has been investigated before. For example, Dobel et al. (2009) trained participants on associations between acoustic words and images of known objects based on their statistical co-occurrence. This untutored associative learning paradigm was expected to mirror the way children and adults acquire new vocabulary for various concepts in an unfamiliar language environment. The degree to which the new words were linked to existing semantic representations was assessed by measuring the N400m magnitude (a MEG response that reflects post-lexical semantic integration). In a crossmodal priming task, participants were presented with pictures of objects they had seen during training (which unfolded across a span of five days, amounting to an overall exposure time of 1.5 hours), preceded by either the object's existing name, a word related to that name, the newly learned word, or a new word with no meaning. The N400m was measured in response to the target picture. Results showed a significant reduction in N400m for the newly learned novel names after training, which resembled the response elicited by existing names and related names, suggesting that this effect was related to the acquisition of meaning and not just exposure to word forms. This indicates that novel words can be rapidly integrated in the semantic system (for corroborating behavioural results, see Breitenstein et al., 2007).

In the context of the present study - and contrasting with Chapter 2 and Chapter 3 - associating nonwords with existing words could facilitate nonwords being integrated into existing conceptual and lexical networks. In connectionist models of language processing (Dell, 1986; Dell et al., 1997; Plaut & Shallice, 1993), the linguistic system can be broken down into three levels of representation: phonological, lexical, and semantic, with each level consisting of individual units that represent a single phoneme, lexical item, or semantic feature. According to this description, not all words will be represented in the linguistic system to the same level. For example, concrete/high imageability would be represented by more stable and numerous features in the semantic system than abstract/low imageability words, and are thus more readily available. This is because imageability refers to the extent to which a word gives rise to a mental image (Tyler et al., 2002a); for example, the word *chair* is more imageable than the word *believe*. Therefore, high imageability/concrete words would have richer and deeper semantic features than low imageability/abstract words (Hill et al., 2014; Sabsevitz et al., 2005).

The richness of semantic features associated to words has been shown to impact the ease with which they can be maintained and recalled in verbal short-term memory (e.g., Bourassa & Besner, 1994). Certainly there is good evidence that vSTM performance is better for high-imageability or concrete words over low imageability or more abstract words, suggesting that items triggering strong representations in the language system correlate with improved performance in vSTM (Acheson et al., 2010; Bourassa & Besner, 1994; Campoy et al., 2015; Kowialiewski & Majerus, 2018, 2020; Majerus & Van der Linden, 2003; L. M. Miller & Roodenrys, 2009; Romani et al., 2008; Savill et al., 2019; Tse & Altarriba, 2007; Walker & Hulme, 1999). Such observations are generally viewed in light of language-based models such as interactive activation models (Dell et al., 1997; N. Martin & Saffran, 1996; McClelland & Rumelhart, 1981), where adjacent levels of the linguistic system (semantic, lexical, and phonological) operate with cycles of feedforward-feedback activation that mediate interaction between semantic and phonological representations of a word. These activations would help to maintain phonological forms strengthened by semantic support stemming from imageability, which could arise in vSTM since richer semantic support spreads through the different layers and provides stronger activation to the phonological system.

Semantic support in vSTM seems to be particularly important in the case of a weak or challenged phonological system. As addressed previously in this thesis, such interactions between the semantic and phonological systems are predicted by connectionist models including the primary systems framework (Patterson & Lambon Ralph, 1999; Plaut et al., 1996; Seidenberg & McClelland, 1989). They consider compensatory mechanisms within the language systems, as demonstrated by neuropsychological studies (Jefferies et al., 2007; Jefferies, Crisp, & Lambon Ralph, 2006; Verhaegen et al., 2013; Wilshire & Fisher, 2004). For example, Verhaegen et al's (2013) paper examined vSTM performance of two aphasic patients: performance at a picture naming task revealed a phonological impairment for one of the patients, and a lexical-semantic language production impairment for the other patient. Verbal short-term memory performance of the patient with phonological weakness was not impacted by phonological frequency, whereas word frequency and lexicality impacted their recall performance. Conversely, the patient with lexical-semantic impairment showed an effect of phonological frequency but no effects of word frequency and lexicality. This indicates that lexical-semantic representations can boost recall when phonological support is insufficient, and that patients with a phonological impairment may be over-reliant on the preserved lexical-semantic system.

Similarly, in language unimpaired individuals, a few studies have found more substantial effects of semantic variables when participants' phonological skills were weak (Savill et al., 2019; see also Strain & Herdman, 1999; Ueno et al., 2014). In Savill et al. (2019), the magnitude of imageability effects across ISR and reading tasks (i.e., relative advantage for high imageability over low imageability words, having controlled for lexical variables like word frequency) was stronger in participants with relatively weaker performance on phonological measures[9], in line with the primary systems hypothesis which proposes a trade-off between phonological and semantic processes, across language domains.

Semantic compensation has been found in participants with developmental dyslexia in reading tasks (e.g., Baddeley et al., 1982; Hennessey et al., 2012; Jorm, 1977), but has never been examined in vSTM tasks. Therefore, the present study took a novel approach to testing the effect of imageability in adults with and without dyslexia, on the assumption that high imageability words would afford stronger semantic activations to otherwise

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[9] All participants in Savill et al, (2019) were students with no reported language difficulties.

unfamiliar nonwords. Verbal short-term memory performance was assessed with an ISR task comprising nonwords that were previously associated to either high or low imageability words in a training task. Similar to Chapter 2 and 3, this training approach should enable the observation of semantic effects that are not induced by phonological familiarity and frequency of use, as suggested by Papagno et al.(2013).

The training manipulation used in this study could be seen as analogous to learning vocabulary in a foreign or second language, i.e., when learning new words in a non-native language, the process often involves associating unfamiliar phonetic constructs (akin to nonwords in this study) with known meanings or concepts (analogous to high or low imageability words) (Nation, 2001). Therefore, a potential benefit of this design is that it is more closely approximating a real-life learning context than Chapters 2 and 3. This method also provides the opportunity to capitalise on the relative advantages certain concepts may have, specifically those with high imageability. High imageability words, with their strong visual or sensory connections, may facilitate the learning process and boost memory performance of associated verbal items more than low imageability words (Caplan & Madan, 2016).

It was predicted that, first, nonwords paired with low imageability words would show a recall advantage over new untrained nonwords in the ISR task. This phonological-lexical effect would demonstrate the effectiveness of the training task and the interaction between long-term knowledge and vSTM. Second, an additional recall advantage for nonwords paired with high imageability words over nonwords paired with low imageability words was expected (i.e., imageability effect), which would indicate that activation of the semantic system supports vSTM, as advocated by language-based models of vSTM (Acheson & MacDonald, 2009b; Majerus, 2013; N. Martin & Saffran, 1996; R. C. Martin et al., 1999). Third, if an imageability effect is detected, and if dyslexic participants rely on semantic representations to compensate their phonological difficulties in vSTM, the magnitude of the imageability effect could be more substantial in dyslexic individuals compared to non-dyslexic individuals.

4.3 Method

Most aspects of the method (task procedure of the psychometric tests and of the ISR task run online on Gorilla, as well as statistical analyses) were identical to the previous study (Chapter 3), except for the following changes and adjustments:

Participants

A different sample from the previous study was simultaneously recruited for the present experiment. Sixty participants (33 females and 27 males) aged between 19 and 45 years (*M* = 31.28, *SD* = 7.59) were recruited via the Prolific and SONA systems. All participants had normal or normal-to-corrected vision and hearing. Thirty-one of the participants had no language or learning difficulties (mean age 32.19 years, *SD* = 9, 18 females) and 29 had a formal diagnosis of dyslexia (mean age 30.31 years, *SD* = 5.73, 15 females). Participants received payment for their participation (£7/hour). Participants gave their informed consent prior to the start of the study. Ethical approval was received from the Psychology Department Ethics Committee at York St. John University.

Psychometric measures

Bayesian Independent t-tests were computed to compare cognitive profiles of the dyslexic and non-dyslexic groups (see **Table 4.1**; same measures as chapter 3). Poorer performance at measures of phonological abilities and nonword reading accuracy (moderate evidence in favour of a group difference for spoonerisms task and decisive evidence in favour of a group difference in accuracy for the ROAR nonword task) was observed for the dyslexic group compared to the non-dyslexic group. Results between groups did not differ for the MaRs-IB matrix reasoning task, the digit span task (forwards and backwards), and for semantic knowledge (measured with the Warrington's graded synonyms task).

Table 4.1. *Psychometric measure results for the dyslexic and the non-dyslexic groups.*

		Dyslexics (n = 29)		Non-dyslexics (n=31)		Bayes factors
Measure		Mean	SD	Mean	SD	BF_{10}
Phonological awareness	**Spoonerisms**[a]	9.07	2.48	10.52	2.37	4.65
Reading	**ROAR**					
	RT-Words	306.06	97.8	282.38	71.63	0.14
	RT-Nonwords	419.51	150.59	351.67	83.28	0.09
	ACC-Words[b]	0.96	0.03	0.97	0.03	1.72
	ACC-Nonwords[b]	0.8	0.13	0.93	0.05	8909.4
Working memory	**Digit Span**[c]					
	Forward	9.72	2.49	10.39	2.75	0.64
	Backward	7.03	3.21	7.94	2.65	0.82
Non-verbal reasoning	**MaRs-IB**[b]					
	ACC	0.52	0.18	0.56	0.15	0.41
Semantic knowledge	**Warrington's graded synonyms**[d]					
	ACC	33.14	8.29	37.71	5.98	1.13

Note. ACC = Accuracy, RT = Response Time (msec), SD = Standard Deviation. Bayes Factors (BF_{10}) > 3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect.

[a] *Maximum score = 12*

[b] *Mean accuracy*

[c] *Maximum score forward = 18, and backward = 16*

[d] *Maximum score = 50*

Stimuli

Nonwords used in Chapter 3 were used in the present experiment (see Appendix C). Instead of novel object images and definitions used in Chapter 2 and 3, 24 English words manipulated for imageability were associated to nonwords. Two sets of 12 high and low imageability monosyllabic words were created following Cortese and Fugett (2004) ratings with high-imageability words > 6 and low-imageability words < 3. Sets were matched for average length, lexical frequency (selected words were low-to-medium frequency according to SUBTLEX-UK Zipf scale van Heuven et al., 2014; see **Table 4.2**), and phonotactic frequency (Vitevitch & Luce, 2004).

***Table 4.2**. Average properties of high and low imageability words.*

Words properties	High-imageability words	Low-imageability words
Imageability rating (1-7)	6.49 (0.24)	2.46 (0.17)
Frequency	3.52 (0.25)	3.60 (0.31)
Number of letters	4.58 (0.67)	4.5 (0.80)
Number of phonemes	3.5 (0.52)	3.83 (0.83)
Summed biphone probability	.008 (.007)	.007 (.005)

Note. Standard deviations in parentheses.

Low imageability words*: bland, urge, crude, brief, graft, funk, fuss, hype, keel brisk, pact, wit*. High imageability words: *broom, bulb, sled, couch, crate, cube, flea, fudge, toad, leech, mall, palm*.

Procedure

Training task

In this task, 12 nonwords were associated to high-imageability words, and 12 other nonwords with low-imageability words. Words were visually presented to mirror the training task used in the previous study. Similar to the phonological training of the previous study, which paired nonwords with images of uncommon objects in the first phase of the training task, each 24 correct word-nonword associations were presented once to the participants. A word appeared on screen simultaneously with its associated auditory nonword and participants were asked to repeat the nonword and to memorise the associations (see **Figure 4.1**). In the second phase of the task, nonwords were presented eight times with the correct word (i.e., associated English word) and four times with a different word (matching the number of presentations of the nonwords in Chapter 3 study). Participants were asked to signal whether the presented association was correct or incorrect by clicking on an icon on screen accordingly, which triggered feedback on accuracy presented on screen for 600ms before the start of the next trial. Thus, each of the 24 nonwords were auditorily presented 12 times in a pseudo-random order, and participants underwent one of the three versions of the task (with nonwords being rotated across the high imageability and low imageability pairing conditions).

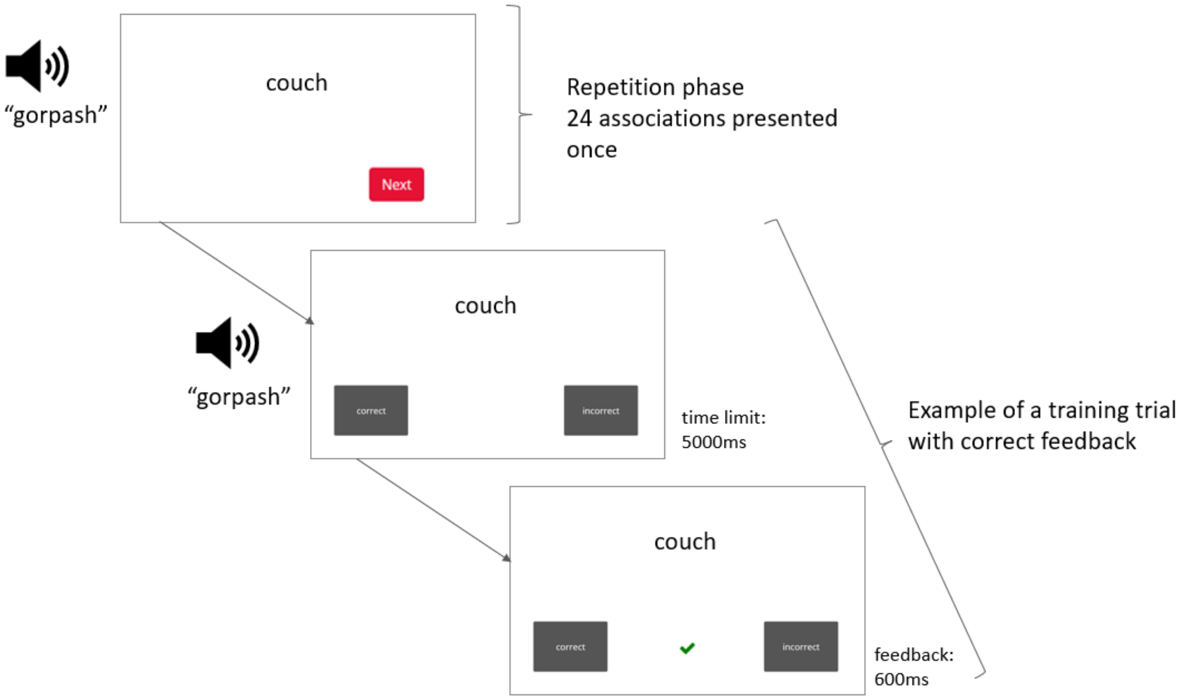

Figure 4.1. *The first segment illustrates an example of a single trial from the repetition phase of the training task. It is followed by a demonstration of an example trial from the subsequent phase of the training task, complete with appropriate feedback upon correct response.*

Learning throughout the training task was assessed by changes in accuracy and reaction times. To ensure that participants learned the association to a reasonable degree, a minimum of 70% accuracy in the last third of trials was necessary. If participants did not reach this accuracy level, they were automatically rejected from the study. Better accuracy and shorter reaction times were expected over the course of the training tasks as a result of learning.

Free recall task

To measure the availability of the phonological forms of trained nonwords, participants had two minutes to orally produce as many nonwords as they could remember from the training task. Responses were digitally recorded and phonologically transcribed to examine whether the availability of lexical and semantic representations benefit their phonological retrieval.

Immediate serial recall task

As in the studies reported so far, in this task participants were asked to repeat lists of four auditory nonwords back in order. There were 54 trials made exclusively of nonwords paired with high imageability words, nonwords paired with low imageability words, and new untrained items presented in a fixed pseudo-random order, which resulted in 18 trials per condition. Nonwords were presented at a rate of 1.25s while an exclamation mark appeared on screen, following which, a question mark prompted participants to recall the nonwords back in order. There were three versions of this task with different list orders to allow for counterbalancing.

As in Chapter 3, in order to avoid cheating and to keep participants motivated, a parallel task was embedded in the immediate serial task. In this task, participants were rarely presented with an image of a blue dot (4 times over the course of the task) and were asked to click on the dot when they saw it appearing. Four dummy trials comprising a blue dot were added to the original 54 ISR trials and were not included in the analyses. These trials contained four nonwords that were not part of the training conditions. This task was intended to encourage participants to keep their hands on the mouse and keyboard and stay focused on the screen, which was thought to prevent writing the nonwords during the encoding phases of the task.

The transcription procedure followed the one used in Chapter 2 and Chapter 3 (and Savill et al., 2017). Each response was manually transcribed phoneme-by-phoneme, and the coding scheme examined the effect of lexical-semantic representations on recall and phonological stability.

Translation task

Analogous to the picture naming task in Chapter 3, the purpose of this task was to assess participants' ability to produce the trained nonwords based on their associated English 'translations'. High and low imageability words from the training task were presented on screen and participants attempted to verbally produce the associated nonword. Words remained on screen until participants pressed a key to proceed to the next trial.

4.4 Results

Training task

Improvement in accuracy and reaction times during the phonological familiarisation task indicated that, by the end of the task, participants effectively learned the word-nonword associations (main effect of trial number on accuracy: $BF_{10} = 4.83*10^{93}$; and on RT: $BF_{10} = 1.71*10^{139}$. See **Figure 4.2**). High and low imageability word-nonword associations were learned to a similar degree (main effect of training condition on accuracy: $BF_{10} = 0.1$; and on RT: $BF_{10} = 0.12$). There was no significant difference between groups (accuracy: $BF_{10} = 0.66$; RT: $BF_{10} = 0.52$). An interaction between trial number and group ($BF_{incl} = 10.32$) showed that a more substantial improvement in accuracy occurred over the course of the training task in the non-dyslexic participants group.

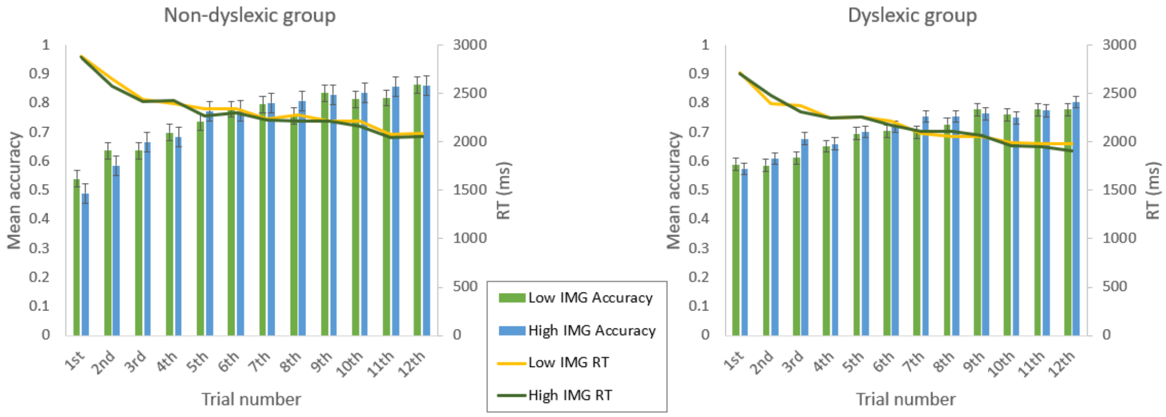

Figure 4.2. *Improvement in accuracy and reaction time for the low imageability-nonword and high imageability-nonword pairings over the course of the training task in non-dyslexic (left panel) and dyslexic (right panel) groups. IMG = imageability. RT = Reaction Time.*

Free Recall

Participants recalled few of the trained nonwords (see **Table 4.3**). When participants generated more than one item, there was weak evidence in favour of an imageability effect ($BF_{10} = 2.58$). Dyslexic and non-dyslexic participants recalled a comparable amount of nonwords ($BF_{10} = 0.7$).

***Table 4.3**. Descriptive statistics for the free recall task. Average number of nonwords recalled (out of 12 per condition).*

Training condition	Group	Mean	SD
High Imageability	Non-dyslexic	3.24	2.10
	Dyslexic	2.52	1.60
Low Imageability	Non-dyslexic	2.55	2.26
	Dyslexic	1.91	1.45

Note. SD = Standard Deviation

Translation task

On average participants generated 22.01% (*SD* = 21.51%) of the correct word's translations. Non-dyslexic participants produced more nonwords than the dyslexic participants (main effect of group: BF_{10} = 6.82). These nonwords were more likely to be produced from the high than from the low imageability condition (main effect of imageability: BF_{10} = 37.37, see **Table 4.4**). There was only very weak evidence in favour of a training condition by group interaction (BF_{10} = 1.12). Independent analyses of the impact of training condition in dyslexic and non-dyslexic groups revealed that there was moderate evidence in favour of an imageability effect in the non-dyslexic group (BF_{10} = 6), and anecdotal evidence for an imageability effect in the dyslexic group (BF_{10} = 1.34).

***Table 4.4**. Mean proportion of nonwords generated in the translation task for dyslexic and non-dyslexic participant.*

Training condition	Group	Mean (%)	SD (%)
High Imageability	Non-dyslexic	34.41	29.25
	Dyslexic	17.53	17.77
Low Imageability	Non-dyslexic	23.92	25.62
	Dyslexic	11.21	11.42

Immediate Serial Recall

Nonword recall performance

Bayesian independent samples t-tests were computed to compare dyslexic and non-dyslexic participants recall accuracy for NEW untrained nonwords. Descriptives statistics show that non-dyslexic participants recalled slightly more NEW nonwords in the correct position compared to dyslexic participants (see **Figure 4.3**), however, Bayes factor (BF_{10} = 1.28) indicated that there was only very weak evidence in favour of the alternative hypothesis.

Nonwords associated with low imageability words

The number of items recalled in *any* position (CAP) was impacted by training (BF_{10} = $4.26*10^6$). More nonwords previously paired with low imageability words were recalled in any position compared to untrained nonwords (see **Figure 4.3**). Recall performance was similar between groups (BF_{10} = 1.26), and there was no interaction between training condition and group (BF_{10} = 0.79).

Analyses of items according to whether they were in the correct position or not confirmed that the overall recall advantage reflected that trained items were more likely to be recalled in the *correct* serial position than new items (BF_{10} =$1.39*10^6$, see **Figure 4.3**), and trained nonwords were more likely to be recalled out of position (BF_{10} = 49.41). Group performance did not significantly differ for those two measures (items recalled in the *correct* position: BF_{10} = 1.56; items recalled in the *incorrect* position: BF_{10} = 0.39), and there was no training by group interaction (items recalled in the *correct* position: BF_{10} = 1; items recalled in the *incorrect* position: BF_{10} = 0.23).

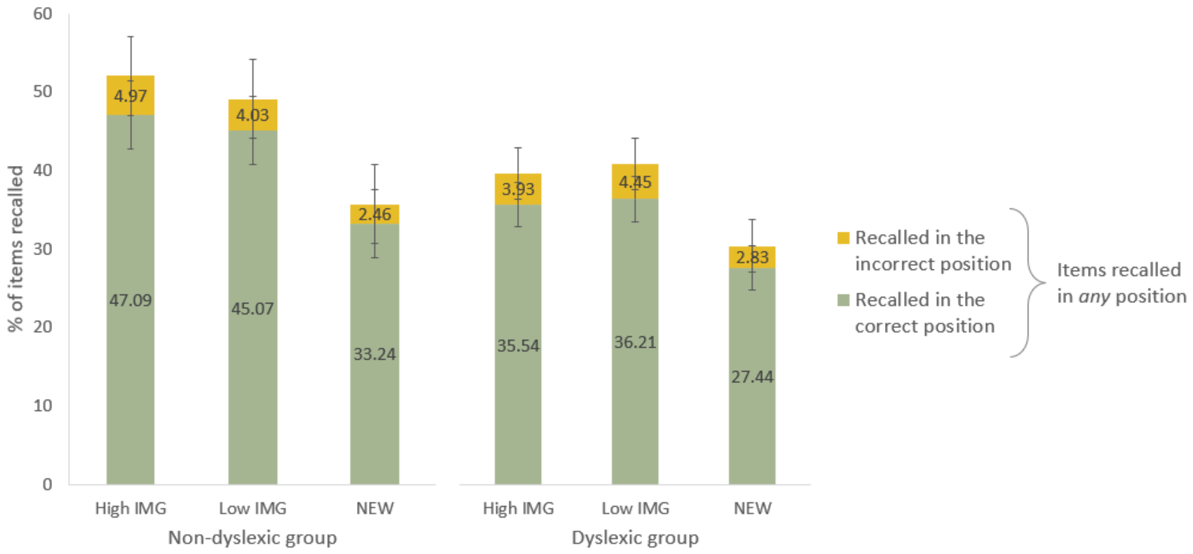

Figure 4.3*. Percentage of items recalled in the correct and incorrect serial position, forming the CAP (items recalled in any position) measure. Non-dyslexic participants are depicted on the left graph and dyslexic participants on the right graph. High IMG = nonwords paired with high imageability words, Low IMG = nonwords paired with low imageability words, NEW = new untrained items.*

Individual analyses of CAP recall performance for both dyslexic and non-dyslexic participants revealed that dyslexic and non-dyslexic participants benefitted from training (dyslexic group BF_{10} = 89.89; non-dyslexic group BF_{10} = 13529.95). Similarly, regarding items recalled in the correct serial position, dyslexic and non-dyslexic participants showed an effect of training (dyslexic group BF_{10} = 59.08; non-dyslexic group BF_{10} = 6203.76). Meanwhile, order errors were influenced by training in the non-dyslexic group (BF_{10} = 4.56), with the dyslexic group showing weaker evidence of such effect (BF_{10} = 2.4).

At the phoneme level, training impacted phoneme migrations (see **Table 4.5**), whereby phonemes from nonwords previously paired with low-imageability words were less likely to migrate to another position compared to phonemes from new untrained items (BF_{10} = 273.52). Again, phoneme migrations were not modulated by group (BF_{10} = 0.8), and there was no group by training interaction (BF_{10} = 0.56). Independent analyses of phoneme migration errors in dyslexic and non-dyslexic groups showed that both groups were influenced by training (dyslexics: BF_{10} = 5.34; non-dyslexics: BF_{10} = 20.20).

Table 4.5. *Mean percentages of phoneme migrations across different training conditions.*

	SEM	FAM	NEW
All participants	11.77 (7.4)	12.23 (9.23)	16.51 (9.91)
Non-dyslexic group	9.59 (7.02)	10.96 (7.81)	14.61 (8.73)
Dyslexic group	14.09 (7.2)	13.59 (10.52)	18.55 (10.82)

Note. Standard Deviations in parentheses.

Nonwords associated with high imageability words

High imageability associations did not have an additional impact on recall relative to low imageability associations; similar recall performance was observed for nonwords from low and high imageability word association lists (BF_{10} = 0.22, see **Figure 4.3**). Non-dyslexic participants recalled more nonwords in any position than dyslexic participants (main effect of group: BF_{10} = 7.76), but there was no training condition by group interaction (BF_{incl} = 0.32).

Similar to results for items recalled in any position, items recalled in the correct serial position and items recalled in the incorrect position measures were not impacted by training condition (BF_{10} = 0.22 and BF_{10} = 0.21 respectively). Participants without dyslexia recalled more items in the correct position than participants with dyslexia (BF_{10} = 6.21), but there was no group difference for items recalled in the incorrect position (BF_{10} = 0.22). There were no interactions between training condition and group (items recalled in the correct position: BF_{incl} = 0.22, or incorrect position BF_{incl} = 0.12).

Independent analyses of dyslexic and non-dyslexic groups showed that there was anecdotal evidence of the *absence* of an effect in the non-dyslexic group for all measures (CAP: BF_{10} = 0.62; CIP: BF_{10} = 0.34; ORD: BF_{10} = 0.46), and moderate evidence in favour of the *absence* of an effect in the dyslexic group for all measures (CAP: BF_{10} = 0.22; CIP: BF_{10} = 0.2; ORD: BF_{10} = 0.24).

At the phoneme level, high imageability associations did not impact phoneme migrations (BF_{10} = 0.21, see **Table 4.5**), suggesting that phonemes from target nonwords associated with high and low imageability words were equally likely to be produced in the wrong position. There was weak evidence in favour of difference between dyslexic and non-dyslexic participants (BF_{10} = 1.32), and no evidence in favour of an interaction between group and high imageability associations (BF_{10} = 0.15).

Relationship with phonological skills

There was no relationship between phonological skills (indexed by the averaged standardised performance at the ROAR nonwords accuracy and spoonerisms tasks) and the magnitude of the training effect (the ratio between CAP for nonwords associated with low imageability words and CAP for new nonwords, r = 0.07, BF_{10} = 0.19, p = .58, see **Figure 4.4**, left panel). Similarly, there was no evidence in favour of a relationship between phonological skill and the magnitude of the imageability effect (i.e., the ratio between CAP performance for nonwords associated with high imageability words and CAP performance for nonwords associated with low imageability nonwords, r = 0.05, BF_{10} = 0.17, p = .71, see **Figure 4.4**, right panel).

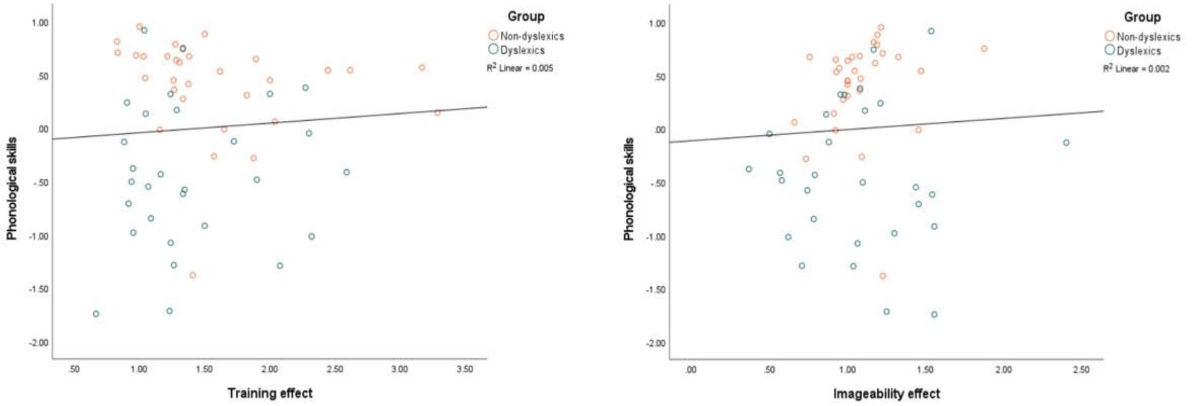

Figure 4.4. *Left graph: relationship between phonological skills and training effect. Right graph: relationship between phonological skills and imageability effect for items recalled in any position at the ISR task.*

4.5 Discussion

This study tried a novel approach to testing the effect of imageability, on the assumption that high imageability words would afford stronger semantic associations to otherwise unfamiliar nonwords. Nonwords were associated with high and low imageability words before their recall in vSTM was measured with an ISR task that comprised lists of nonwords previously paired with low imageability words, nonwords paired with high imageability words and new nonwords that were not paired with words. It was expected that nonwords associated with low imageability words would show an advantage compared to new nonwords, and that vSTM span for nonwords paired with high imageability could be better than for nonwords paired with low imageability words.

In addition, dyslexic participants were expected to demonstrate a relatively greater impact of high imageability associations compared with non-dyslexic participants.

Similar to Chapter 2 and Chapter 3, a substantial effect of phonological training was found. That is, irrespective of the type of trained associations, previous auditory exposure to nonwords benefited their recall in vSTM across all measures of vSTM including item level, item order and phoneme order recall, indicating that phonological familiarity improves vSTM span. This effect could be due to phonological exposure to the nonwords, resulting in phonological representations of the items which support recall vSTM. That is, during the training task of the experiment, the phonological system was able to rapidly learn some of the phoneme sequences associated with nonwords. This partial learning allowed the phonological system to develop pattern completion properties, which enabled it to predict or activate some of the phonemes that were grouped together as an item in the ISR task. In other words, the phonological system was able to anticipate the phonemes that would follow and activate them before they were presented in the task. This gave the participants an advantage when recalling the nonwords associated with low imageability words compared to entirely new items. The improved verbal short-term memory capacity for nonwords associated with low imageability words suggests that the pattern completion properties developed during the training task phase facilitated the retrieval of information from long-term memory. Overall, this finding highlights the important role that pattern completion plays in the phonological processing of nonwords and how it can enhance vSTM capacity.

In addition, since nonwords were associated with existing English words, it is likely that the updated lexical representations played a role in the enhancement of vSTM. The effect of lexicality in vSTM is one of the strongest psycholinguistic effects and is widely documented (Hulme et al., 1991, 1995; Majerus & Van Der Linden, 2003; Roodenrys & Hulme, 1993). The presence of associated lexical-semantic knowledge may provide a stabilising effect on an item's phonemes. This means that when an individual is presented with a familiar word, it is processed and stored as a single chunk, rather than as multiple units. This contrasts with unfamiliar nonwords, which lack a pre-existing lexical-semantic association, and are instead represented as a sequence of phonemes that are processed separately. As a result, when attempting to recall an unfamiliar nonword, individuals may struggle to group together the individual phonemes into a cohesive whole, as there is no pre-existing representation to guide this process. Overall, these findings highlight the importance of the interplay between lexical-semantic knowledge and vSTM processing.

Contrary to what was predicted (assuming trained associations were rapidly integrated into LTM), recall performance for nonwords associated with high-imageability words did not differ from performance for nonwords associated with low-imageability words. Previous studies have found direct effects of imageability on recall performance when using lists of words (Acheson et al., 2010; Chubala et al., 2018; Kowialiewski & Majerus, 2018; L. M. Miller & Roodenrys, 2009; Romani et al., 2008; Savill et al., 2019; Walker & Hulme, 1999). Highly imageable words are thought to gain more substantial feedback for higher levels of linguistic representation as predicted by interactive activation models (Dell et al., 1997; N. Martin & Saffran, 1997; McClelland & Rumelhart, 1981). One important difference between the present study and previous studies that found an imageability effect on vSTM, of course, is the ISR task comprised nonwords that were previously associated with high and low imageability words; not the words themselves. This novel design allowed the exact same phonological exposure to the nonwords, and that way, was meant to differentiate effects of phonological familiarity from semantic effects. However, for any semantic effects to emerge in vSTM, high levels of learning of word-nonword associations were necessary, which may not have been achieved in the present study.

Contrasting with Chapter 2 and 3 where nonwords paired with semantic information were learnt at a higher level than nonwords that were not associated with meaning, high and low imageability nonword associations were learnt at a comparable level in both groups in the present study. It appears that words associated with low imageability were not as disadvantaged as associations between nonwords and blurred images (Chapters 2 and 3). An important consideration related to this could be the homogeneity in the format of the word pairings across different conditions. Whereas the process of learning associations with blurred images might have posed a greater challenge compared to those with clear images in Chapter 3.

In Duyck et al. (2003), learning performance of high and low imageability word nonword associations was similar when items were visually presented, and better for nonwords associated with high imageability words when word-nonword associations were presented auditorily in children. In addition, high and low imageability pairs were differentially impacted by articulatory suppression (i.e., overloading working memory by, for example, saying ‘the’ repeatedly whilst encoding the item pairs, which prevents the use of verbal working memory). Visual representations elicited by high imageability words seem to have a protective effect on the learning of item associations under articulatory suppression, possibly because high imageability words can be encoded through mental imagery, whereas low imageability words can rely on phonological encoding strategies only, since no visual representation would be available. These results show that visual codes are important for new word acquisition and were likely to be more salient between conditions in Chapter 2 and 3 than in the present study, which could explain the lack of difference in learning high and low imageability words-nonword associations.

Associating nonwords with images of existing objects has been shown to be an effective way to allow for the integration of novel word forms with existing semantic information (e.g., Dobel et al., 2009; Hawkins et al., 2015). However, by definition low imageability words do not have clear visual representations. It was thus not possible to use an image-nonword association paradigm in the present study. In addition, it should be noted that in Dobel et al. (2009), nonword-image associations benefited from 1.5 hours of exposure overall, which was significantly more than word-nonword associations in this study (i.e., the training task lasted approximately 30 minutes).

Similarly, as pointed by Dagenbach et al. (1990), extensive training is needed for obscure unknown words to be semantically integrated and linked to existing words. Here, it could be that the associations between items were episodic instead of established semantic representations. This could explain why, in the ISR task, an effect of training was found (i.e., better recall performance for nonwords associated with low imageability words compared to new nonwords), but with no difference between nonwords associated with high, compared to low, imageability words. Since little meaning became available after training, both nonword conditions activated lexical-phonological representations and would symbolise the acquisition of associative knowledge instead of semantics. Alternatively, lexical competition could have occurred in the ISR task, whereby the effect of nonword associations was dampened by more established forms (i.e., the existing words), which does not help with phonological maintenance in vSTM.

A number of limitations to interpretation can be identified in the present study. First, despite the choice of high imageability words having been driven by careful control of variables such as imageability, frequency and phonotactic probability, some of the selected words may not have been optimally imageable. For example, the word *flea* may not give rise to a precise mental image compared to the word *geese* because of its small size and lack of distinctiveness. Second, as discussed above, the written presentation of words in the training task may not have been the ideal modality for their association with auditory nonwords (however see Schweppe & Rummer, 2016 who suggest that written text presentation can support long-term learning). This is particularly relevant for dyslexic participants whereby the reading component and verbal demands of training and translation tasks may have been the grounds for the dyslexic group's poorer performance at the translation task, which was a mean to assess the acquisition of word-nonword associations. More precisely, in the training task, non-dyslexic participants showed greater improvement in accuracy than dyslexic participants. It follows that non-dyslexic individuals demonstrated significantly better recognition performance than dyslexic participants at the translation task.

Paired associate learning (i.e., the ability to establish arbitrary connections between two stimuli that can be verbal and/or visual requiring pairing a stimulus and a response item in memory) has been found to be related to reading difficulties and dyslexia (Clayton et al., 2018; Hulme et al., 2007; Kalashnikova & Burnham, 2016; Litt et al., 2013; Litt & Nation, 2014; Messbauer & de Jong, 2003; Vellutino et al., 1975; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001). More specifically, difficulties in learning phonological forms appears to influence the performance of school-aged children with dyslexia in visual-verbal and verbal-verbal paired association tasks (Litt & Nation, 2014; but see Hulme et al., 2007 for a general deficit in associative learning account). This deficit can be explained by difficulties in phonological processing that are typically found in individuals with dyslexia (e.g., Snowling & Hulme, 1994b), and can affect a range of tasks such as reading, vSTM, speech production and perception. No strong conclusions can be drawn from the present study because of the lack of overall group difference in the training task; however, it is likely that the reading and verbal components of the training and the translation tasks were particularly taxing for dyslexic participants.

In sum, this study examined the contribution of long-term linguistic representations on vSTM by adopting a novel training approach where nonwords were associated with high and low imageability words. A robust recall advantage was found for trained nonwords compared to new untrained nonwords, both in dyslexic and in non-dyslexic groups, suggesting that phonological familiarity with newly acquired phonological forms improves vSTM span. The lack of difference between recall performance of nonwords associated with high and low imageability words can be explained by various methodological limitations, such as the choice of high imageability words and their written presentation in the learning phase, or the lack of integration of these new forms in semantic networks, perhaps reflecting relative differences in initial learning and consequent lexical availability from LTM, rather than a semantic effect *per se*. Therefore, the next study focused on relative semantic effects in short-term memory without training tasks, to avoid the potential caveats they entail. Even though training nonwords in previous studies allowed for investigating semantic effects irrespective of phonological familiarity and frequency, they are premised upon successful integration and establishment of representations in semantic long-term memory, which might not have fully occurred in the present study.

Chapter 5.

Rapid semantic effects in short-term memory? Effects of word imageability and semantic associations in dyslexic and non-dyslexic adults

Open Science Framework link: http://osf.io/cjf2m/

5.1 Abstract

It is well-established that long-term lexical and semantic knowledge associated with words advantages recall of their phonological codes in verbal short-term memory (vSTM), as assessed in immediate serial recall (ISR) tasks. However, the nature of semantic influences on vSTM, for example, whether they reflect automatic or entirely strategic processes, remains an open question. It has been suggested, based on a fast encoding running span procedure intended to prevent strategic processes, that long-term linguistic effects on vSTM are mostly not reliant on strategy – with an exception for semantic effects of word imageability (which Kowialiewski & Majerus, 2018, only observed under standard ISR testing conditions). Since vSTM literature has typically used standard (slow) ISR presentation, and much theorising related to semantic effects has relied upon manipulations of imageability, the present study set out to assess whether such lexical-semantic variable effects would hold in speeded ISR conditions (with limited encoding time). Furthermore, it examined whether the relative size of effects would vary as a function of phonological skills (given previous correlations with imageability; Savill et al., 2019). Manipulations of imageability and semantic relatedness tested in regular ISR conditions were compared with those tested under speeded conditions, with dyslexic and non-dyslexic individuals. Results showed that lexical-semantic effects were consistent across experiments: better recall performance for high compared to low imageability word lists, and for semantically related, compared to unrelated, word lists, was found irrespective of presentation rate. These effects were also similar in magnitude for dyslexic and non-dyslexic participants, although the imageability effect was larger when

phonological capacity was weaker under fast presentation rate. Thus, given the preservation of effects in fast-encoding conditions, semantic knowledge effects in ISR tasks, like imageability, are unlikely to be entirely dependent on slow presentation and deployment of recall strategies, as predicted by language-based accounts of vSTM.

5.2 Introduction

The impact of long-term information related to word meaning on recall performance is apparent in verbal short-term memory (vSTM), similarly to the way in which other aspects of language processing are impacted by the linguistic system (e.g., Acheson & MacDonald, 2009b; Patterson et al., 1994; Romani et al., 2008). Language-based models envisage vSTM arising through reactivation between phonological, lexical, and semantic representations assisted by interactive activations (Majerus, 2013; N. Martin & Saffran, 1997; Patterson et al., 1994), which echoes primary systems/connectionist approach of language processing, assumed to reflect interactions between phonology and semantics (the primary systems hypothesis, Patterson & Lambon Ralph, 1999; Plaut et al., 1996). According to such perspectives, the semantic system is central to language processing (contrary to multi-component models, e.g., Baddeley, 2000) and can support the phonological system if it is weak or unstable. This assumption has been investigated in reading with dyslexic individuals, who, as a result of poor phonological skills, may rely more strongly on lexical-semantic variables (Hennessey et al., 2012; A. de P. Nobre et al., 2016; van der Kleij et al., 2019). Similarly, normal readers with weaker phonological skills - indexed by poorer nonword reading – showed greater semantic reliance than participants with better phonological skills, suggesting that phonological abilities might predict semantic reliance in reading (Woollams et al., 2016). These results were further supported in vSTM tasks in which the magnitude of the imageability effect was found in relation to phonological skills under standard immediate serial recall (ISR) conditions (Savill et al., 2019). Relatively increased imageability effects in participants with weaker phonological skills were interpreted according to the primary systems hypothesis, that allows for stronger support from semantic representations when phonological support is less available.

Previous chapters investigating semantic effects in vSTM independently of phonological familiarity in dyslexic and non-dyslexic individuals have yielded mixed results, with semantic effects that were not always observed, potentially due to insufficient associative links between nonwords and their meaning (i.e., multimodal representations in Chapter 2 and Chapter 3, and English 'translations' in Chapter 4). While attempts for previous studies to train nonwords allowed excellent control of phonological familiarity between semantically trained and phonologically familiarised nonwords - important for isolating the contribution of phonological-lexical and semantic representations - the manipulations were necessarily premised upon successful integration and establishment of semantic representations in long-term memory, which might not have fully occurred. Indeed, it seems plausible that the integration and establishment of new semantic representations in long-term memory may not have been fully achieved, a factor which could explain the absence of a relationship between phonological skill and the effect of newly trained semantic representations in vSTM. This underlines a critical issue in the methodology, where the depth and strength of these semantic links may not have been sufficiently robust to bring about the expected effects. Thus, examining the effect of established semantic representations in vSTM in dyslexic and non-dyslexic adults - without the uncertainty that the learning phase induced in the previous chapters - is sensible, and was the primary aim of the present study.

Manipulations of imageability and semantic relatedness are commonly used to examine the influence of word-level semantic information, with a recall advantage for high over low imageability words (Acheson et al., 2010; Campoy et al., 2015; Castellà & Campoy, 2018; Chubala et al., 2018; L. M. Miller & Roodenrys, 2009; Romani et al., 2008; Walker & Hulme, 1999), and semantically related over unrelated words (Kowialiewski & Majerus, 2018; Monnier et al., 2011; Poirier & Saint-Aubin, 1995; Tse, 2009). Notwithstanding, it is important to consider *how* these semantic variables affect vSTM, since through different semantic knowledge for the semantic relatedness and the imageability effects, support will occur at a different level. An obvious distinction is that advantages for semantically related words will stem from inter-item associative knowledge of shared features across items held in vSTM (see Dell et al., 1997; 'dress' and 'shirt' are more semantically related than 'dress' and 'snail'), whereas high imageability words, which embody richer and more consistent semantic features than low imageability words (Binder et al., 2009; Hill et al., 2014; Roxbury et al., 2014; Sabsevitz et al., 2005; Yap et al., 2015), will benefit from individual item-level semantic knowledge.

Following a language-based STM perspective, in both cases - by virtue of interactions between lower (i.e., the phonological level) and higher levels of representations (i.e., the semantic level) - semantic activation would spread down to the lexical and phonological levels, supporting the activation of phonological nodes which are otherwise at risk of rapid decay. Therefore, inter-item and item-level semantic knowledge, reflected by semantic relatedness and imageability, would help to produce correct phonological responses in vSTM tasks. However, they are likely to do so in slightly different ways. In the context of semantic relatedness, words with shared features activate lexical and semantic nodes, which reactivate each other via interactive activation. This leads to strong activations for related, compared to unrelated, items during encoding (Kowialiewski & Majerus, 2020). The imageability effect occurs in a similar way – through redundant activations between semantic and lower levels – yet because individual items do not share common semantic features, they do not benefit from between-item reactivation arising in the semantic association effect. Hence, language-based views of vSTM assume that the impact of linguistic knowledge arises early and quickly when items are encoded. In contrast, accounts that distinguish long-term memory from vSTM suggest that psycholinguistic effects emerge at the point of recall (Baddeley, 2000; Hulme et al., 1991; Schweickert, 1993b), through implementation of encoding strategies such as rehearsal (silently repeating the items), or semantic elaboration (using the meaning of the items to remember or connect them), both of which gain from longer inter-item intervals (Shulman, 1970). Drawing on these theoretical perspectives, the speed of item presentation in ISR tasks becomes a useful variable in assessing whether these effects are time-dependent or more automatic processes.

The presentation rate of items in ISR tasks is typically one item per second (e.g., Hoffman et al., 2009; Hulme et al., 1991; Jefferies, Frankish, et al., 2009; Majerus et al., 2007; N. Martin & Saffran, 1997) or even slower (e.g., Chapters 2, 3 & 4, Savill et al., 2015, 2017). However, studies investigating whether the imageability effect is a time dependent and slow, or a more automatic process, have found inconsistent results (Campoy et al., 2015; Kowialiewski & Majerus, 2018; Shulman, 1970). In a seminal study, Shulman (1970) used a probe recognition task to investigate phonemic and semantic encoding in vSTM with different presentation rates. That is, a probe recognition task in which a synonym or a homonym of one of the presented items was used to force participants to encode words phonemically and semantically. Lists of 10 words were presented in fast (1 word/350ms) and slow (1 word/1400ms) presentation rates. In this study, a recall advantage was found for words in the semantic encoding condition under slow presentation rates, suggesting that semantic effects are associated with slow, time dependent encoding strategies. Following Shulman (1970), Campoy et al. (2015) examined whether imageability effects in vSTM are a consequence of slow presentation rates (as suggested by Shulman) – assumed to further strategic semantic encoding. They compared recall performance for high and low imageability words in a standard ISR task (whereby words are presented at a rate of 1 item per second) and in slow ISR (1 item per 2 seconds). Similar to Shulman (1970), the imageability effect seemed to benefit from strategic elaboration allowed by slow presentation rate. However, in a second and third experiment, the imageability effect was maintained in dual task paradigms, reducing strategic encoding processes by involving a concurrent, attention-demanding task (i.e., a random time interval generation task in experiment 1 and visuo-spatial tasks in experiment 2). Since visuo-spatial interference may prevent the elaboration of mental images at encoding, it could reduce semantic encoding of high imageability words, hence these results suggest that the effect of imageability might not solely arise from strategic elaboration (i.e., semantic elaborative processes).

Most relevant to the present study, in Kowialiewski & Majerus (2018), most long-term linguistic effects on vSTM were found not to rely on strategy as they arose in a fast (2.5 items per second) encoding running span procedure. In this task, participants listened to rapidly presented sequences of items that can include up to 3-4 items per second and these sequences vary unpredictably in length. Following each list, participants were asked to recall the items they remember, which usually includes the most recently presented items from the sequence. This procedure reduces strategic processes by preventing strategic rehearsal and inter-item grouping strategies (Bunting et al., 2006; Cowan, 2001; see also Pham & Archibald, 2022). However, while most semantic manipulations survived this task context, when examining the effect of imageability, Kowialiewski and Majerus (2018) found that it only appeared under standard ISR conditions (1 item per 1.5 seconds) that gave the opportunity for words to be strategically encoded. They concluded that surface-level effects of lexicality, word frequency and semantic relatedness are automatic, as suggested by language-based accounts, whereas imageability effects rely on deeper semantic knowledge, requiring strategic encoding and time to arise in vSTM. These findings question the use of word imageability as a proxy for semantic knowledge given it could rely on distinct underlying processes from other linguistic variables. This is a salient consideration in the context of literature examining individual differences in semantic sensitivity drawing upon imageability as a primary manipulation (such as Savill et al., 2019). Therefore, further investigation into the impact of presentation rate on semantic effects in vSTM could shed light on the conditions under which different types of semantic knowledge come into play.

The present study attempted to investigate semantic relatedness and imageability effects further by comparing ISR recall performance for these effects with standard ‘slow’ (1 item per second) and fast (2 items per second) presentation rates. This aimed to determine whether these effects are preserved under speeded conditions, as would be predicted by language-based views of vSTM, envisaging effects initially arising via automatic activation. This was tested in two Experiments: Experiment 1 examined imageability effects in vSTM (i.e., using lists of high and low imageability words in ISR) by extending and adapting the ISR task from Savill et al. (2019), whereas Experiment 2 assessed effects of semantic relatedness in vSTM (i.e., using ISR lists of semantically related and unrelated words). In addition, based on the primary systems hypothesis (Patterson & Lambon Ralph, 1999), the study attempted to examine relative effects of semantic variables in dyslexic and non-dyslexic participants. Another significant aim of this study was to examine whether relationships found between phonological skills and semantic effects are an artefact of the traditional ISR format.

The involvement of linguistic representations in vSTM should manifest as a main effect of the ISR list condition (i.e., better recall accuracy for high imageability compared to low imageability words, and better recall accuracy for semantically related compared to unrelated lists, both in non-dyslexic and dyslexic groups). On the one hand, in Experiment 1, if the imageability effect is reliant on slow presentation rates and conscious processes, then speeding up presentation time should reduce the imageability effect in both groups (Campoy et al., 2015; Kowialiewski & Majerus, 2018; Shulman, 1970). This could manifest as an interaction between presentation rate and imageability, and possibly as an absence of main effect of imageability in the fast presentation rate of ISR. On the other hand, if the effect of imageability in vSTM is more automatic, then it should be of a similar magnitude under fast and slow presentation rates in both groups. This would be demonstrated by a significant main effect of imageability across both ISR tasks, devoid of any interaction between imageability and presentation rate. In Experiment 2 (where semantic relatedness is manipulated), semantic effects were expected to arise both in the slow and the fast presentation rate ISR tasks, since they have been previously found to occur automatically (Kowialiewski & Majerus, 2018).

In addition, relative phonological weakness in the dyslexic group (which is assessed by performance in standardised psychometric tasks), was expected to be reflected by the emergence of group differences in recall performance (but the pattern of these differences is somewhat open ended): These could manifest as a main effect of group (overall, poorer recall performance in the dyslexic than the non-dyslexic group; which would likely correspond with poorer digit span performance) and/or as a stronger effect of list condition on recall in the dyslexic group (following associations with increased semantic reliance with decreasing phonological capacity). Finally, when examining semantic effects based on participants' phonological skills - independently of their diagnosis of dyslexia – greater semantic effects were expected to be associated with weaker phonological performance.

5.3 Experiment 1

Gorilla Experiment Builder (www.gorilla.sc) was used to design and host the present study. All ISR tasks procedure included trials to provide an attention check, following recommendations for attention checks as a quality criterion for online data collection (Sauter et al., 2020). Additional psychometric measures were collected for participant screening and descriptive/interpretive purposes (as per the studies in previous chapters); they are not key outcome measures.

The investigation was divided into two experiments delivered in separate Prolific sessions. Experiment 1, focused on the impact of word imageability and presentation rate in vSTM tasks, while Experiment 2, which involved a subset of participants who returned from Experiment 1, examined the effects of semantic relatedness and presentation rate. As such, the methods and results for each experiment are now discussed individually. This maintains the distinct focus of each experiment, allowing for detailed analysis and understanding of each aspect under investigation.

Experiment 1: Method

Participants

Sixty-two participants, including 32 participants with a formal diagnosis of dyslexia aged between 19 and 43 years (*M*=29.25, *SD*=7.44), and 30 participants without a diagnosis of dyslexia aged between 18 and 45 years (*M*=28.77, *SD*=8.2), took part in the experiment. All participants were native English speakers with no history of neurological disorders. Participants were recruited via the University online recruitment system, Prolific, and the University community. They gave their written informed consent (for both experiments) prior to their participation in the study and received payment (£7/hour) or course points for their participation. Participants were required to have Google Chrome installed to access the experiment for its established stability with the Gorilla platform. The study had been approved by the York St. John ethics committee.

Psychometric measures

Psychometric measures that could be adapted for use within the Gorilla.sc online environment were used to establish participants' cognitive profiles: phonological awareness was assessed with an electronic version of the Spoonerism test from the York Adult Assessment Battery-Revised (Warmington et al., 2013). Sight word efficiency and phonemic decoding efficiency were assessed with an adapted version of the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999), which tests the number of words and nonwords correctly read aloud from a list within 45s. The Digit Span Task (adapted by M. Turner & Ridsdale, 2004) was used to assess verbal working memory. Semantic knowledge was assessed via an electronic version of Warrington's Graded Synonyms (Warrington et al., 1998). Finally, to provide with a control measure, non-verbal reasoning was assessed with the Matrix Reasoning Item Bank (MaRs-IB, Chierchia et al., 2019).

Table 5.1. *Psychometric measures for Experiment 1.*

		Dyslexics (n = 32)		Non-dyslexics (n = 30)		t values		Bayes factor
Measure	Test	Mean	SD	Mean	SD	t (60)	*p*	BF_{10}
Phonological awareness								
	Spoonerism	8.43	2.66	9.87	2.50	2.17	.02	3.58
	TOWRE							
	Words	77.81	12.23	88.93	10.00	3.90	< .001	206.00
	Nonwords	48.47	8.31	59.70	4.06	6.69	< .001	$2.14*10^6$
Working Memory								
	Digit Span							
	Forward	8.81	2.65	10.83	2.47	3.11	.001	25.51
	Backward	6.53	1.65	8.30	2.22	3.58	< .001	85.53
Non-verbal Reasoning								
	MaRs-IB							
	ACC	27.59	5.65	29.70	8.46	1.16	.71	0.46
Semantic Knowledge								
	Synonyms							
	ACC	34.13	4.40	34.31	5.33	0.14	.89	0.26

Note. SD = Standard Deviation, RT = Reaction Time (msec), ACC = Accuracy. Bayes Factors (BF_{10})>3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect.

As expected, and following previous chapters, dyslexic participants performed more poorly than non-dyslexic participants on measures of phonological skills and working memory (see **Table 5.1**). A phonological score was derived from the average of spoonerism task and TOWRE nonword scores. Despite score overlap between dyslexic and non-dyslexic participants (see **Figure 5.1**), there was decisive evidence in favour of an effect of group, with phonological scores of non-dyslexic participants being better than those of dyslexic participants (BF_{10} = 6676). The two groups' performance did not differ at measures of semantic knowledge and non-verbal reasoning.

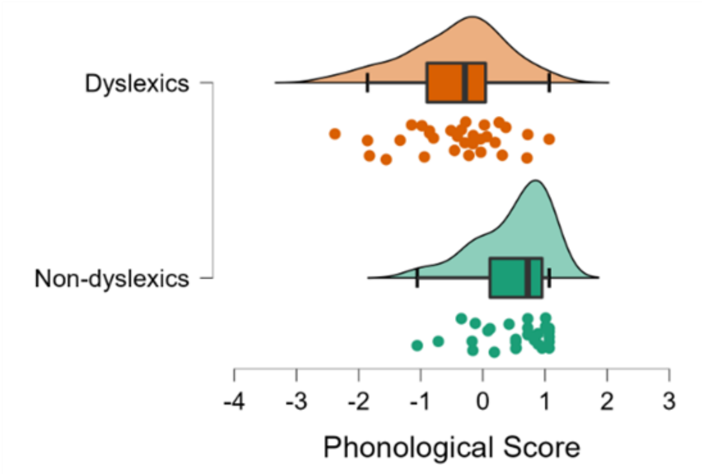

Figure 5.1. *Raincloud plots for phonological scores (y axis) of dyslexic and non-dyslexic participants (x axis).*

Experimental Stimuli

The original ISR items from Savill et al. (2019) were used in the first ISR experiment with standard ('slow') presentation rate (see Appendix D, Table D1). These consisted of 260 low-to-medium frequency words (according to Van Heuven et al., 2014, SUBTLEX-UK Zipf frequencies) with a CVC structure. Half of these words were high imageability and the other half were low-imageability (according to Cortese & Fugett, 2004, high imageability rating > 4, and low imageability rating < 3.5; see **Table 5.2**). High and low imageability word sets were matched for frequency and length. There were 40 ISR lists of 6 and 7 words each (20 lists per imageability condition) without phoneme repetitions at each syllable position. An additional set of 90 nonwords were designed by recombining phonemes from each word list, to generate 10 nonword lists of four and 10 nonword lists of five items.

Table 5.2. *Mean characteristics of each experimental condition in the slow and fast immediate serial recall tasks.*

Stimulus properties	Standard 'slow' presentation rate ISR (stimuli form Savill et al., 2019)			Fast presentation rate ISR (matched set)			Stimulus comparison (BF_{10})		
	High-imageability words	Low-imageability words	Nonwords	High-imageability words	Low-imageability words	Nonwords	High-imageability words	Low-imageability words	Nonwords
Imageability rating (1-7)	5.8 (0.66)	2.83 (0.54)	N/A	5.84 (0.6)	2.83 (0.52)	N/A	0.14	0.14	N/A
Frequency	3.50 (0.38)	3.49 (0.68)	N/A	3.58 (0.43)	3.45 (0.61)	N/A	0.42	0.15	N/A
Letters	4.23 (0.73)	4.18 (0.75)	4.57 (0.78)	4.08 (0.70)	4.12 (0.70)	4.37 (0.64)	0.43	0.16	0.82
Syllables	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)			
Phonemes	3.00 (0.00)	3.00 (0.00)	3.00 (0.00)	3.00 (0.00)	3.00 (0.00)	3.00 (0.00)			

Note. Standard deviations in parentheses. IMG = Imageability

For the second ISR task employing the fast presentation rate, a new set of 130 words, each with high and low imageability, was carefully curated using the procedure outlined by Savill et al. (2019) (see Appendix D, Table D2). These words were matched to the original set in terms of frequency and phonemic length, with each word containing three phonemes. Additionally, another set of 130 words from the original set used in the standard 'slow' ISR task, split evenly between high and low imageability, was selected. This approach aimed to minimise repetition and maintain the novelty of the items used in each task. Immediate serial recall word sets were matched for imageability ratings, frequency, and length (see **Table 5.2**). All 90 nonwords from the original stimuli set were replaced by a new set of nonwords created by recombining the phonemes of the new word list.

Stimuli were rerecorded by a British female speaker, and pronounced to approximately 500ms in length; the length was further normalised to 500ms in Praat (6.2.14) without changing pitch.

Procedure

Before the start of the experiment, participants completed an equipment check, ensuring that their audio and voice recording were functioning properly. First, participants took part in the ISR task with standard ‘slow’ presentation rates (1 word per second, as per Savill et al., 2019). During this task, participants were instructed to repeat the auditorily presented lists, and to recall as many items as possible in the order of presentation. An instruction screen informed participants about the to-be-recalled number of items and was presented at the beginning of each block. In each list, an exclamation mark was displayed on screen for the duration of audio presentation, after which a question mark prompted participants to recall the items back.

There were two practice trials and 20 six-item word lists, 10 low imageability and 10 high imageability lists, which were pseudorandomly presented, followed by 10 lists of four nonwords. After a rest break, there were 10 lists of five nonwords and 20 lists of seven items (10 low and 10 high imageability pseudorandomly presented). Once the participant finished their list recall attempt (responses were recorded as individual audio files within Gorilla.sc), participants clicked on an arrow on screen to proceed to the next list trial. An embedded parallel task required participants to detect a rarely presented blue dot on screen (four times over the course of the task) by clicking on the dot when they saw it appearing. The corresponding dummy trials were not included in analyses. Once the first standard ‘slow’ ISR task was completed, participants completed the second ISR task with fast presentation rate (2 items per second) testing the second matched set of stimuli. All other aspects of this task were identical to the first ISR (i.e., with standard ‘slow’ presentation rate). Verbal recall responses were subsequently phonemically transcribed offline by trained coders.

The screening psychometric measures were completed following the two ISR tasks, and these were followed by a final questionnaire that was administered to gain insight about potential strategies used to complete the ISR tasks (Dunlosky & Kane, 2007; Logie et al., 1996) and about the environment in which participants completed the experiment. Specifically, participants were asked if they associated a visual image to the words, remembered the items in groups, focused on the meaning of the words, or employed other strategies to aid memory during the slow ISR task. The same questions were reiterated after the fast ISR task. Subsequently, participants were asked whether the environment in which they completed the experiment was sufficiently quiet and free of distractions. Finally, participants were provided with a debrief and were informed about the details of the second experiment.

Experiment 1: Results Analysis strategy

All Bayesian analyses were performed using the default wide Cauchy prior distribution of $r = \sqrt{2}/2$ (Bouffier et al., 2022; Kowialiewski & Majerus, 2018), as per previous chapters.

To begin, the recall accuracy of nonwords (i.e., nonwords recalled in the correct serial position) was analysed. This served as an initial measure of basic recall capacity for items wihtout lexical-semantic support, for comparison between dyslexic and non-dyslexic participants.

The second analysis focused on items recalled in any position (CAP; i.e., items recalled irrespective of serial order) as a function of group (non-dyslexic vs. dyslexic participants), presentation rate (slow vs. fast) and item condition (high- vs. low-imageability). For precision, recall performance was also divided into items recalled in the *correct* serial position and for items recalled but not in the correct serial position (order errors). Independent analyses of dyslexic and non-dyslexic CAP performance in the slow and the fast ISR tasks were also planned to verify the strength of the imageability effect in each group.

In addition, for this experiment, phoneme level analyses were conducted to examine the effect of imageability on phoneme migrations (i.e., the presence of phonemes from the target list that were recalled in an incorrect order yet maintained their original syllabic position in relation to the target.). By identifying these particular errors, we could potentially gain insights into influences on the phonological processing and sequencing of the target items. The phoneme migration measure was calculated as a percentage of the total of target phonemes, allowing for the assessment of phonological coherence of the response and quantify phoneme order errors, which depend on the total number of phoneme targets recalled. Similar to item level analyses, independent analyses of dyslexic and non-dyslexic production of phoneme migrations in the slow and fast ISR tasks were planned to verify the strength of the imageability effect in each group.

Finally, to account for group heterogeneity in phonological performance and following Savill et al. (2019), correlations between CAP nonword z scores and imageability index for each participant (ratio between high and low imageability CAP scores) in the fast and slow ISR conditions were computed. In addition, correlations between phonological skills (indexed by the averaged spoonerisms and TOWRE nonword z scores) and the imageability index were examined to verify whether the imageability effect depends on general phonological skills assessed with standardised tests.

Experiment 1: Results

Do dyslexic and non-dyslexic participants nonword recall performance differ?

A Bayesian ANOVA of group and presentation rate performed on nonword recall data showed that there was anecdotal evidence in favour of a main effect of group (BF_{10} = 1.53, see **Figure 5.2**), and no evidence for a main effect of presentation rate (BF_{10} = 0.68). Moreover, no interaction was identified between group and presentation rate (BF_{incl} = 0.64).

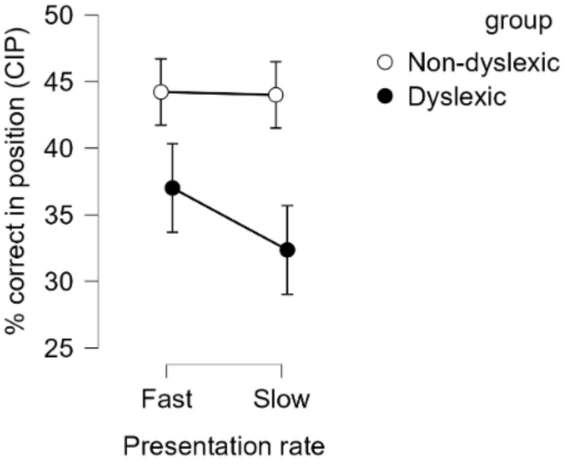

Figure 5.2. *Percentage of nonwords recalled in the correct position (CIP) for the fast and slow ISR tasks in the dyslexic and non-dyslexic groups.*

Independent analyses of the participants recall accuracy in the slow and fast ISR tasks revealed that non-dyslexic participants recalled more nonwords in the correct position compared to dyslexic participants in the slow presentation rate ISR - the effect was supported by strong evidence (BF_{10} = 6.26). There was anecdotal evidence in favour of a between-group difference in the fast presentation rate ISR (BF_{10} = 1.08).

How robust is the imageability effect under speeded conditions?

An analysis of recall performance as a function of item condition, presentation rate, and group found decisive evidence in favour of an effect of imageability ($BF_{10} = 1.65*10^{15}$) on items recalled in any position (see **Figure 5.3**). Recall performance was reliably better for high-imageability compared to low-imageability words. Dyslexic and non-dyslexic participants reached similar levels of performance, and presentation rate did not impact recall, as demonstrated by inconclusive evidence for the effects of presentation rate ($BF_{10} = 0.86$), and group ($BF_{10} = 1.01$) on items recalled in any position. There were no interactions between group and presentation rate ($BF_{incl} = 0.16$); group and item condition ($BF_{incl} = 0.19$); item condition and presentation rate ($BF_{incl} = 0.27$); and group, presentation rate and item condition ($BF_{incl} = 0.08$).

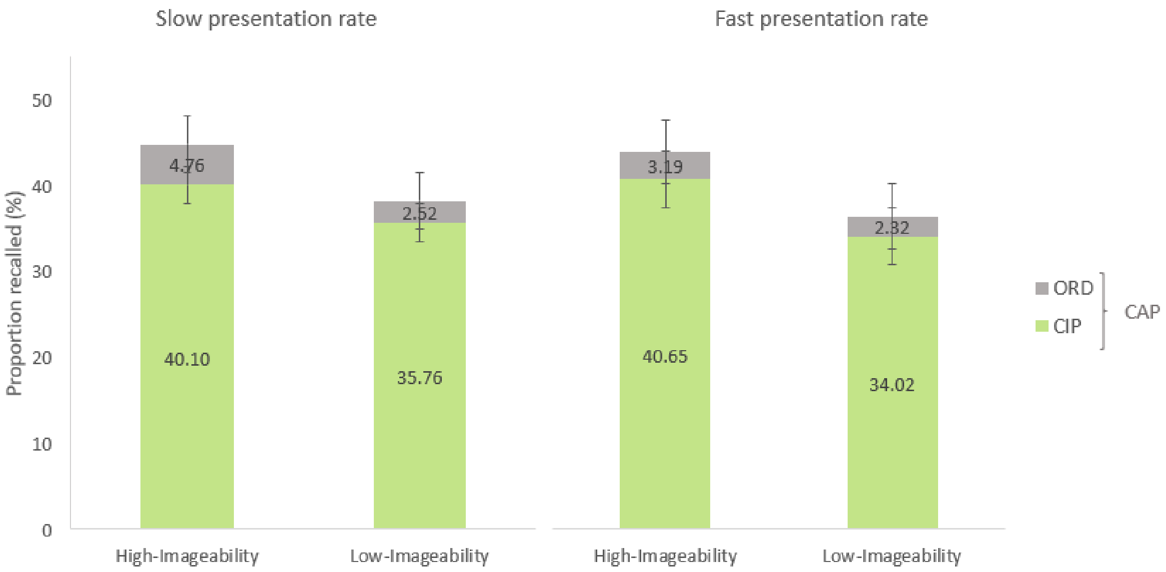

Figure 5.3. *Proportion of items recalled in the correct serial position (CIP), and order errors (ORD) representing items recalled in any position (CAP) for high and low imageability words, in the slow and fast presentation rate ISR.*

The items recalled in any position measure comprises items recalled in the correct serial position and items recalled in the incorrect serial position. As shown in

Table 5.3, high-imageability items were more likely to be recalled in the *correct* serial position, compared to low-imageability words. This imageability effect was supported by decisive evidence with $BF_{10} = 2.22*10^{11}$. There was weak evidence for an effect of group for items recalled in the correct position ($BF_{10} = 1.60$), and no effect of presentation rate (BF_{10} = 0.39). No interactions were found for items recalled in the *correct* position (group × item condition: BF_{incl} = 0.4; presentation rate × group: BF_{incl} = 0.22, item condition × presentation rate: BF_{incl} = 1.3).

High-imageability items were more likely to be recalled in the *incorrect* serial position compared to low-imageability words (BF_{10} = 52599). There was an effect of presentation rate whereby more items were recalled in the *incorrect* position in the slow presentation rate condition than in the fast condition (BF_{10} = 14.06), and no effect of group (BF_{10} = 0.35). For items recalled in the *incorrect* position, the imageability effect was more substantial in the slow than in the fast presentation rate condition (item condition × presentation rate: BF_{incl} = 45.16). No interactions were found for items recalled in the incorrect position between group and item condition (BF_{incl} = 0.34), and between presentation rate and group (BF_{incl} = 0.43).

Table 5.3. *Items recalled in any position, in the correct and incorrect positions descriptive statistics and Bayesian t-test comparisons between high and low imageability words in the slow and fast ISR conditions.*

Item Recall	Group	Presentation rate	Imageability condition	Mean	SD	Comparisons (BF_{10})
	Non-Dyslexics	Slow	High	48.23	14.25	6003.61
			Low	40.97	15.65	

Recalled correct in position (CAP)		Fast	High	47.59	13.88	$1.03*10^6$
			Low	40.13	14.77	
	Dyslexics	Slow	High	41.71	13.2	3272.4
			Low	35.75	11.55	
		Fast	High	40.31	13.49	$1.93*10^6$
			Low	32.79	11.47	
Recalled correct in position (CIP)	Non-Dyslexics	Slow	High	43.59	14	40.83
			Low	39	15.81	
		Fast	High	44.72	13.86	969228.51
			Low	37.54	14.88	
	Dyslexics	Slow	High	36.83	13.22	51.91
			Low	32.72	11.55	
		Fast	High	36.83	12.84	82600
			Low	30.72	11.43	
Recalled in the incorrect position (ORD)	Non-Dyslexics	Slow	High	4.64	2.76	741.14
			Low	1.97	1.88	
		Fast	High	2.87	2.07	0.25
			Low	2.59	1.81	
	Dyslexics	Slow	High	4.88	3.22	23.94
			Low	3.03	2.1	
		Fast	High	3.49	2.92	9.92
			Low	2.07	2.2	

The independent analysis of CAP recall performance for both dyslexic and non-dyslexic participants in slow and fast presentation rate tasks underscored the presence of an imageability effect across both rates. The magnitude of this effect was observed to be relatively similar for both groups and it intensified under the fast presentation rate condition, as visualised in ***Figure 5.4*** *and detailed in*

Table 5.3.

When items were recalled in the correct serial position, there was very strong evidence favouring the imageability effect under the slow presentation rate, while under the fast presentation rate, the evidence was decisive. This outcome was consistent across dyslexic and non-dyslexic participants (see

Table 5.3).

Regarding order errors under the slow presentation rate condition, there was decisive evidence in favour of an imageability effect for non-dyslexic participants, and strong evidence in favour of such an effect in the dyslexic group (see

Table 5.3). In both groups, high imageability words were recalled in the wrong position more frequently than low imageability words. However, in the fast presentation rate condition, while dyslexic participants exhibited moderate evidence of the imageability effect, non-dyslexic participants did not display any discernible difference.

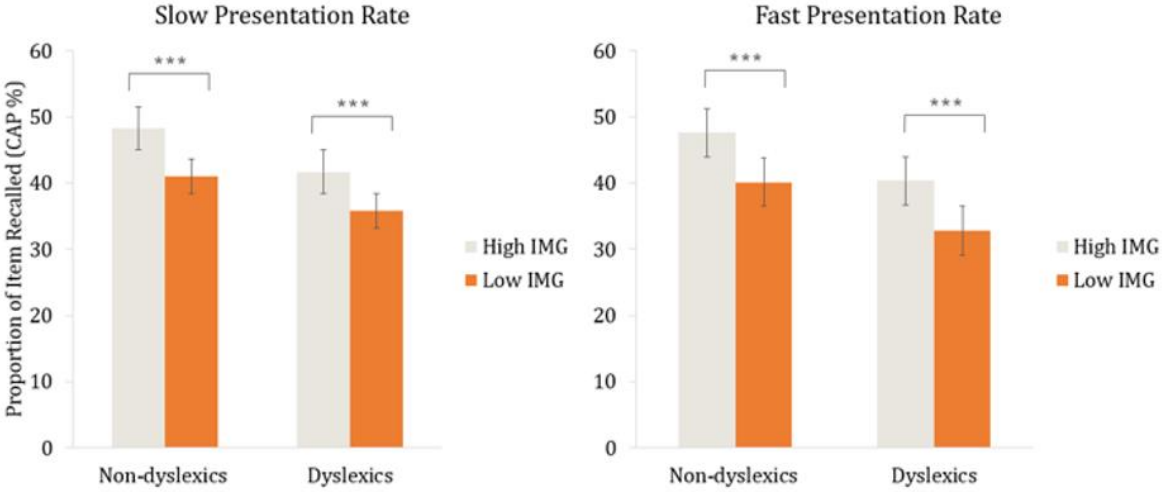

Figure 5.4. *Proportion of items recalled in any position (y axis) from high imageability and low imageability word lists across the dyslexic and non-dyslexic groups (x axis), in the slow presentation rate (left graph), and in the fast presentation rate conditions (right graph). IMG = Imageability*

Phoneme level analyses

Analyses of phoneme migrations showed that phonemes from high imageability words were less likely to migrate than phonemes from low imageability words (main effect of imageability: $BF_{10} = 2.67*10^8$). Presentation rate also influenced phoneme migrations, whereby item phonemes were more likely to migrate in the fast than in the slow presentation rate ($BF_{10} = 7655.13$).

Participants with and without dyslexia produced the same amount of phoneme migrations ($BF_{10} = 0.76$). There was weak evidence in favour of an interaction between the imageability manipulation and presentation rate: the effect of imageability on phoneme migrations was more substantial in the slow than in the fast presentation rate ($BF_{10} = 2.32$, see **Figure 5.5**). There were no interactions between group and imageability effect ($BF_{10} = 0.36$), and between presentation rate and group ($BF_{10} = 0.66$).

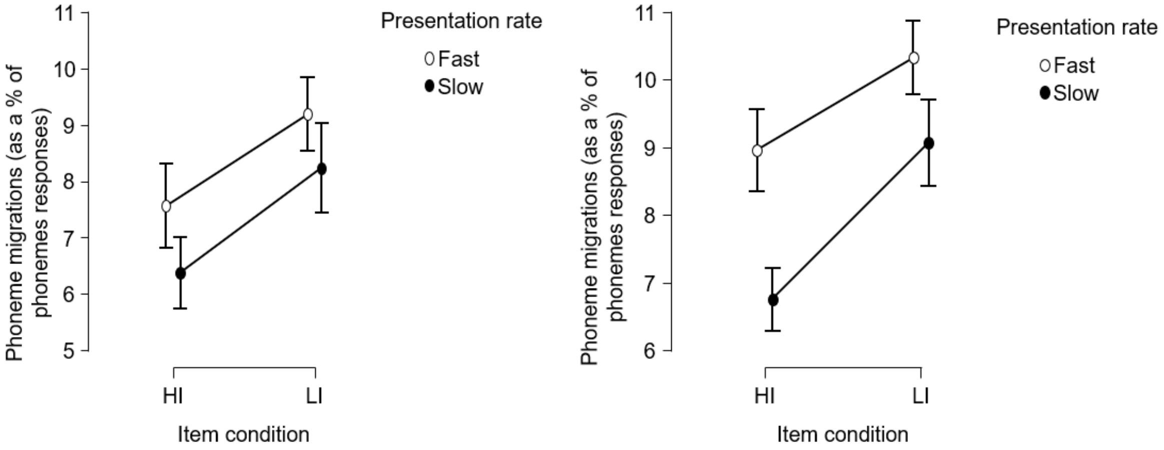

Figure 5.5. *Percentage of phoneme migrations in the non-dyslexic and dyslexic groups.*

Group analyses of phoneme migrations highlighted the presence of an imageability effect in both dyslexic and non-dyslexic groups. The imageability effect was more pronounced in the dyslexic group, with a higher rate of phoneme migrations in low imageability lists than high imageability ones (non-dyslexic group: BF_{10} = 127.65; dyslexic group: BF_{10} = 276163.3). The faster presentation rate increased the production of phoneme migrations in both groups (non-dyslexic group: BF_{10} = 3.24; dyslexic group: BF_{10} = 1542.22).

Notably, for phoneme migrations, an interaction between the imageability effect and presentation rate was only discernible in the dyslexic group (non-dyslexic group: BF_{10} = 0.95; dyslexic group: BF_{10} = 14.08). This suggests that dyslexic participants demonstrated a more prominent imageability effect under the slower presentation rate compared to the faster rate.

Does the relationship between the imageability and phonological skills replicate?

Correlations between CAP nonword z scores and imageability effect indicated that, in the fast presentation rate ISR task, participants with poorer nonword performance showed stronger imageability effects (r = -0.36, p = .004, BF_{10}= 9.43). In the slow presentation rate condition, weak evidence supported the relationship between nonword performance and imageability effects (r = -0.27, p = .03, BF_{10} = 1.43, see **Figure 5.6**).

There was no evidence in favour of a relationship between phonological skills (indexed by the averaged spoonerisms and TOWRE nonword z scores) and the imageability index under fast presentation rate (*r* = -0.22, p = .09, BF_{10}= 0.67) and slow presentation rate (*r* = 0.05, p = .68, BF_{10}= 0.17, see **Figure 5.6**),

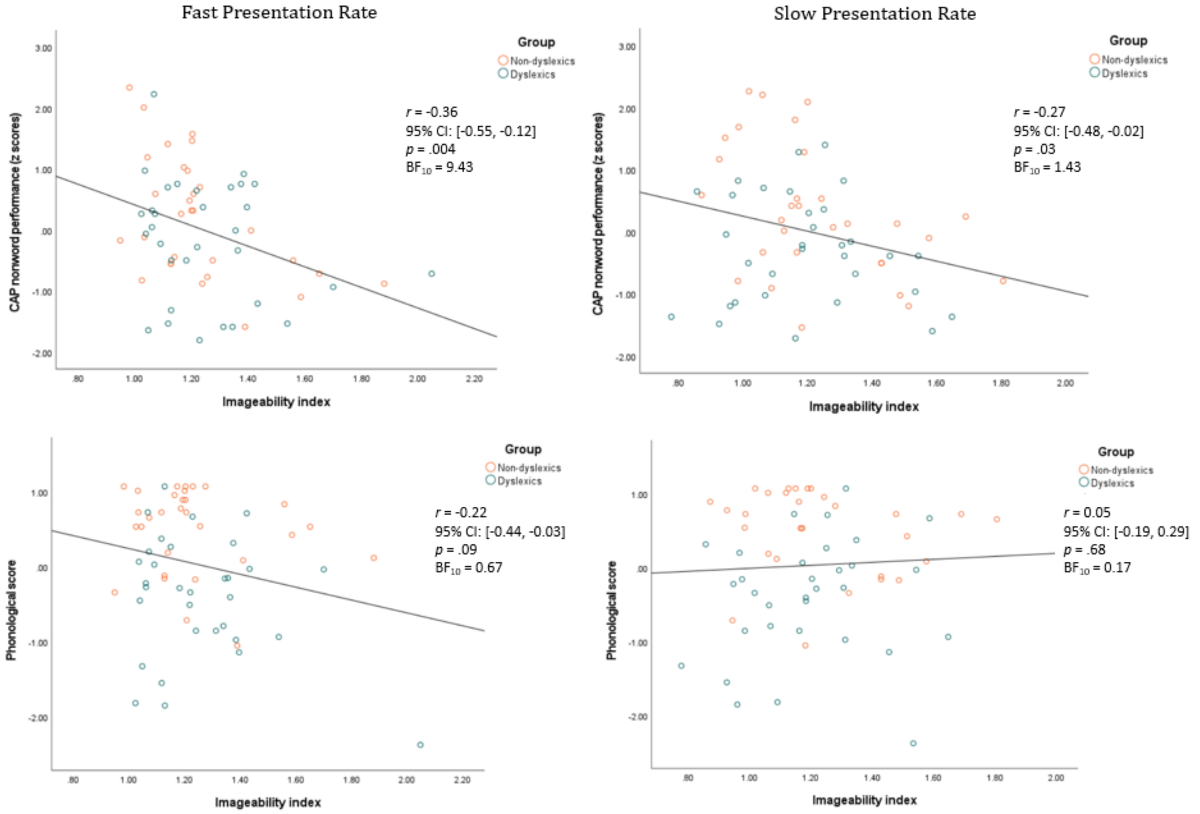

Figure 5.6*. Correlations between CAP nonword performance z scores and the imageability index in the fast and slow presentation rate ISR tasks (top panel), and correlations between phonological skills (indexed by the averaged spoonerisms and TOWRE nonword z scores) and the imageability index (bottom panel).*

Experiment 1: Summary

Experiment 1 examined whether the imageability effect in ISR was preserved under speeded conditions, and whether the relative size of effects varied as a function of phonological skills and dyslexia. A key finding was that the imageability effect was preserved under fast encoding conditions, suggesting that it does not depend entirely on slow presentation and recall strategies. The observation of a higher frequency of order errors under the slow presentation rate aligns with the notion that the additional time available in the slower rate allows for more strategic manipulation, thus increasing the likelihood of such errors compared to the fast presentation rate (Saint-Aubin & Poirier, 1999a). Interestingly, rates of phoneme migrations were affected by imageability (fewer with higher imageability), suggesting that semantic support contribute to the coherence of the phonological trace, as predicted by the semantic binding hypothesis. Consistent with the findings of Savill et al. (2019), participants with relative weakness in phonology – indexed by nonword performance - showed more substantial effects of imageability, particularly under speeded ISR conditions.

In Experiment 2, the well-established advantage of semantic relatedness and its relationship with presentation rate was examined. Specifically, the impact of item-item associations in vSTM was compared between dyslexic and non-dyslexic participants under both rapid and standard 'slow' ISR conditions.

5.4 Experiment 2

Experiment 2: Method

Participants

Fifty-one participants from Experiment 1 subsequently completed Experiment 2. These comprised 26 non-dyslexic participants aged between 18 and 44 years (*M* = 29.77, *SD* = 9.41), and 25 dyslexic participants aged between 19 and 43 years (*M* = 28.68, *SD* = 7.41).

Psychometric measures

Since this experiment comprised the same participants, the cognitive profile of this subgroup was similar to that of Experiment 1, with better performance in phonological measures and working memory tests for the non-dyslexic participants, and equivalent non-verbal reasoning and semantic knowledge performance (see **Table 5.4**).

Table 5.4. *Psychometric measures for Experiment 2.*

		Dyslexics (n = 32)		Non-dyslexics (n = 30)		t values		Bayes factor
Measure	Test	Mean	SD	Mean	SD	t (60)	*p*	BF10
Phonological awareness								

	Spoonerisms	8.00	3.00	10.04	2.38	2.70	.005	9.89
	TOWRE							
	Words	78.64	12.77	88.88	10.46	3.14	<.001	25.97
	Nonwords	49.16	8.28	60.00	3.10	6.02	<.001	103998
Working Memory								
	Digit Span							
	Forward	8.56	2.18	10.92	2.38	3.69	<.001	100.89
	Backward	6.56	1.76	8.54	2.23	3.51	<.001	63.40
Non-verbal Reasoning								
	MaRs-IB							
	ACC	28.28	5.98	29.19	7.95	0.46	.65	0.31
Semantic Knowledge								
	Synonyms							
	ACC	34.08	3.55	34.76	5.61	0.50	.62	0.32

Note. SD = Standard Deviation, RT = Reaction Time (msec), ACC = Accuracy. Bayes Factors (BF_{10})>3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect. These values are shown in bold.

Experimental Stimuli

For the first (standard 'slow' presentation rate) ISR task, a set of 270 monosyllabic words was selected from a word association database (De Deyne et al., 2018), to form 90 semantically related triplets, similar to the method used by Kowialiewski and Majerus (2018) (see Appendix D, Table D3). Semantic associations between three stimuli were either taxonomic (i.e., relations between the words were abstract, based on shared features, e.g., red – pink – grey), or thematic (i.e., concrete relations, based on co-occurrence of events or scenarios, e.g., milk – cow – farm). Lists of two, three and four triplets were designed to produce 10 lists of six, nine and 12 words. Following Kowialiewski and Majerus (2018), the same stimuli were randomly recombined to generate semantically unrelated lists, so that words that belonged to the same semantic category did not appear in the same lists. To minimise item repetition in the second (fast presentation rate) ISR task, half of the stimuli from Experiment 1 were kept, with the remaining replaced by a new set of 45 triplets (see Appendix D, Table D4). The slow and fast stimulus sets were matched for imageability ratings, frequency, and number of phonemes and letters (see **Table 5.5**). In total, for each ISR task (i.e., slow and fast) within the semantically related condition there were 10 lists of two triplets forming six-item lists (e.g., "rain – cloud – storm – hand – foot – arm"), 10 lists of three triplets forming 9 item-long lists (e.g., "red – pink – green – east – north – south – milk – cow – farm"), and 10 lists of four triplets forming 12-item lists (e.g., “mime – clown – act – gas – leak – oil – song – tune – voice – pearl – shine – gem”). For the unrelated condition there were 10 lists of 6 unrelated words (e.g., “shape – ill – yarn – tease – bus – jar), 10 lists of nine unrelated words, and 10 lists of 12 unrelated words. Related and unrelated list conditions were pseudorandomly presented within each list length (6, 9, and 12 items).

All stimuli were recorded by a native British female speaker and their length was normalised to 500ms in Praat (6.2.14) in the same conditions as Experiment 1.

Table 5.5. *Average Stimulus Properties and Bayesian t-test Comparisons for the Slow and Fast Immediate Serial Recall Tasks Stimuli for Experiment 2 with semantically associated words.*

Stimulus properties	Slow ISR words	Fast ISR words	Bayes Factor (BF_{10})
Imageability rating (1-7)	5.04 (1.35)	5.00 (1.36)	0.1
Frequency	4.45 (.75)	4.43 (.8)	0.1
Phonemes	3.63 (.55)	3.66 (.53)	0.11
Letters	4.12 (.76)	4.2 (.82)	0.18

Note. Since the semantically related words were reorganised into semantically unrelated lists, semantically related and unrelated sets were completely matched for all properties. BF_{10} values < 1 provide evidence in favour of the null hypothesis. ISR = Immediate Serial Recall

Procedure

One day after completing Experiment 1, participants completed the second experiment consisting of two ISR tasks with pseudorandomly-presented lists of semantically related triplets and unrelated words. The instructions were the same as Experiment 1: In the first ISR task with slow presentation rate (1 item/second), participants were asked to verbally repeat the auditorily presented word lists, and to recall as many words as possible in the order of presentation. An instruction screen informed participants about the to-be-recalled number of items, which was presented at the beginning of each block. In each list, an exclamation mark was displayed on screen for the duration of audio presentation, after which a question mark signalled participants to repeat the items. After completing two practice trials, participants tried to recall 60 experimental lists consisting of 30 semantically related word lists and 30 unrelated word lists presented with no more than two serial repetitions of the same list condition. The different list lengths were presented in blocks starting with ten six-item lists and increasing to nine and then 12. Finally, participants took part in the ISR task using the second set of stimuli with words presented at the faster rate (2 words per second). The same questionnaire used at the end of Experiment 1 was then administered to participants.

Experiment 2: Results

The analyses followed the same principle as Experiment 1, except for phoneme level analyses, which could not be performed in the present experiment due to the impossibility of designing lists of semantically related words without phoneme repetitions. To compare the relative impact of imageability and semantic relatedness as a function of presentation rate, an additional analysis compared recall accuracy in Experiments 1 and 2. A supplementary analysis was conducted to examine the effect of semantic relatedness based on list length, and is provided in Appendix E.

Analyses of recall performance based on item condition, presentation rate, and group, showed found decisive evidence in favour of an effect of semantic relatedness on items recalled in any position (BF_{10} = $7.32*10^{25}$). As expected, recall performance was better for semantically related, compared to unrelated, word lists (see **Figure 5.7**). There was inconclusive evidence for an effect of group (BF_{10} = 0.56), weak evidence for an effect of presentation rate (BF_{10} = 1.44), and an anecdotal interaction between group and presentation rate (BF_{incl} = 1.09) indicating that non-dyslexic participants demonstrated comparable recall performance in both slow and fast ISR tasks. However, this was not the case for dyslexic participants, who showed a decline in recall performance when the ISR was faster, as compared to when it was slower. There were no interactions between group and item condition (BF_{incl} = 0.47); item condition and presentation rate (BF_{incl} = 0.46); or group, presentation rate and item condition (BF_{incl} = 0.06).

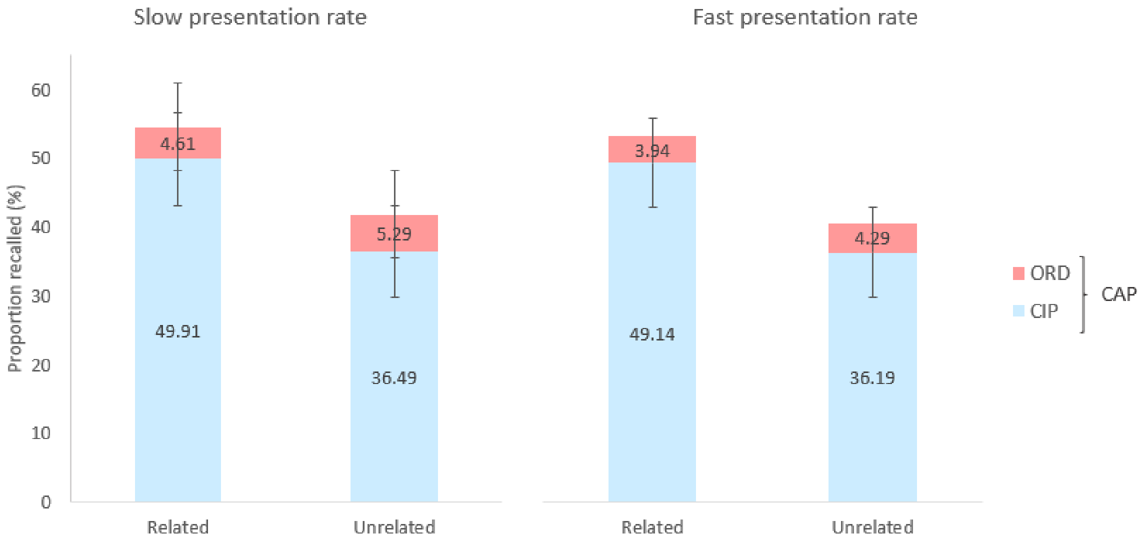

Figure 5.7. *Proportion of items recalled in the correct serial position (CIP), and order errors (ORD) representing items recalled in any position (CAP) for semantically related and unrelated words, in the slow and fast presentation rate ISR.*

An effect of semantic relatedness on items recalled in the *correct* position was observed ($BF_{10} = 3.59*10^{24}$, see **Table 5.6**), and no effect of group was detected for this measure (BF_{10} = 1.03). There was no effect of presentation rate (BF_{10} = 0.24) and no interactions (group x item condition: BF_{incl} = 0.62; presentation rate x group: BF_{incl} = 0.33), item condition x presentation rate: BF_{incl} = 0.25).

Evidence for an effect on items recalled in the *incorrect* serial position was inconclusive (BF_{10} = 0.66). On average, only 4.5% of the words were recalled in the incorrect position, with no group effect observed for this measure (BF_{10} = 0.35). More items were recalled in the *incorrect* position in the slow, rather than fast, presentation rate task (BF_{10} = 5.37). No interactions emerged for items recalled in the *incorrect* position between item condition and presentation rate (BF_{incl} = 0.24), between group and item condition (BF_{incl} = 0.14), and between presentation rate and group (BF_{incl} = 0.34).

Table 5.6*. Items recalled in any position, in the correct and incorrect positions descriptive statistics and Bayesian t-test comparisons between semantically related and unrelated word lists in the slow and fast ISR conditions.*

Item recall	Group	Presentation rate	Semantic condition	Mean	SD	Comparisons (BF10)
Recalled in the correct position (CAP)	Non-Dyslexics	slow	related	56.18	10.11	$7.29*10^{9}$
			unrelated	43.01	9.52	
		fast	related	55.94	11.04	$2.2*10^{10}$
			unrelated	42.91	9.88	
	Dyslexics	slow	related	52.79	9.52	$1.42*10^{12}$
			unrelated	40.49	8.75	
		fast	related	50.12	11.33	$1.22*10^{9}$
			unrelated	37.97	8.59	
Recalled in the correct position (CIP)	Non-Dyslexics	slow	related	51.94	9.6	$6.91*10^{10}$
			unrelated	37.99	9.38	
		fast	related	52.22	10.14	$1.16*10^{10}$
			unrelated	38.36	9.14	
	Dyslexics	slow	related	47.79	8.23	$2.94*10^{10}$
			unrelated	34.92	8.23	
		fast	related	45.94	10.18	$7.17*10^{8}$
			unrelated	33.94	7.48	
Recalled in the wrong position (ORD)	Non-Dyslexics	slow	related	4.25	2.85	0.52
			unrelated	5.01	3.04	
		fast	related	3.72	2.2	0.85
			unrelated	4.54	3.24	
	Dyslexics	slow	related	4.99	2.74	0.31
			unrelated	5.57	3.39	
		fast	related	4.18	3.09	0.22
			unrelated	4.03	2.36	

Note. SD = Standard Deviation.

An independent group analysis of recall performance for items Correct in Any Position (CAP) and items Correct in Position (CIP) under both slow and fast presentation rate tasks revealed a consistent effect of semantic relatedness across the rates for both dyslexic and non-dyslexic participants. As depicted in **Figure 5.8**, and detailed in **Table 5.6**, this effect is supported by decisive evidence in both participant groups. However, no impact of semantic relatedness on order errors was observed among dyslexic and non-dyslexic participants.

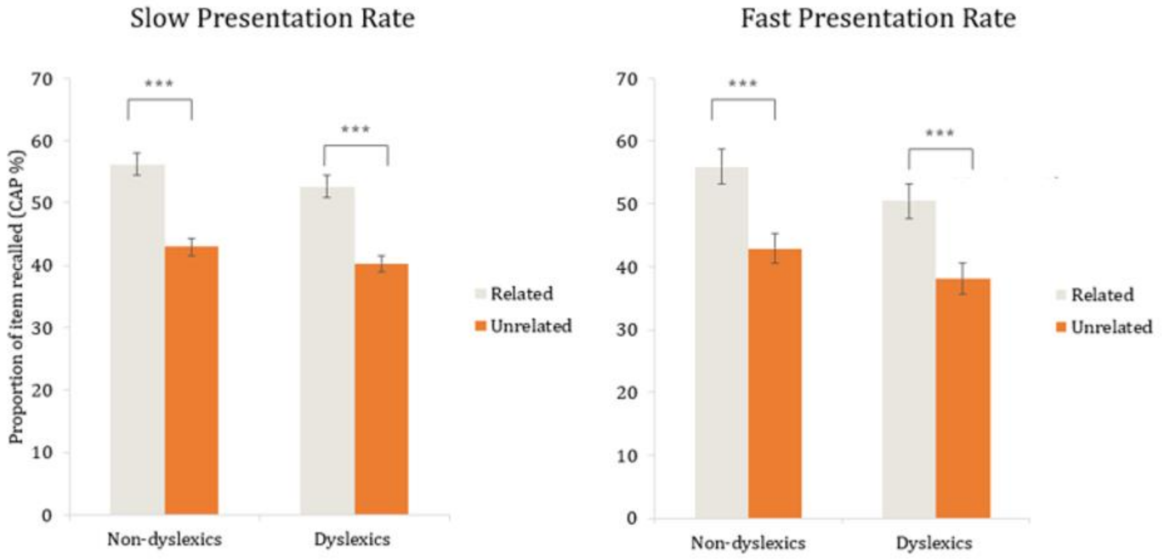

Figure 5.8. Proportion of items recalled in any position (y axis) from semantically related and unrelated lists across dyslexic and non-dyslexic groups (x axis), in the slow presentation rate (left graph), and in the fast presentation rate conditions (right graph).

Relationship between phonological skills and the effect of semantic relatedness

Similar to Experiment 1, the relationship between semantic index (i.e., the ratio between semantically related and nonrelated CAP scores) and nonword CAP performance z scores (taken from Experiment 1, since no nonword lists were included in this experiment, which was completed by the same participants); as well as correlations between the effect of semantic relatedness and phonological skills (i.e., the averaged spoonerisms and TOWRE nonwords z scores) in the fast and slow presentation rate conditions were analysed. In the fast presentation rate condition, there was anecdotal evidence supporting a negative correlation between nonword performance and semantic effect whereby participants with weaker nonword performance showed stronger effects of semantic relatedness (r = - 0.28, p = .05, BF_{10} = 1.12). There was moderate evidence *against* this relationship in the slow presentation rate condition (r = 0.003, p = .98, BF_{10} = 0.18). No evidence was found in favour of a relationship between phonological scores and semantic effects in the fast presentation rate condition (r = - 0.13, p = .37, BF_{10} = 0.26), and in the slow presentation rate (r = 0.05, p = .71, BF_{10} = 0.19, see **Figure 5.9**).

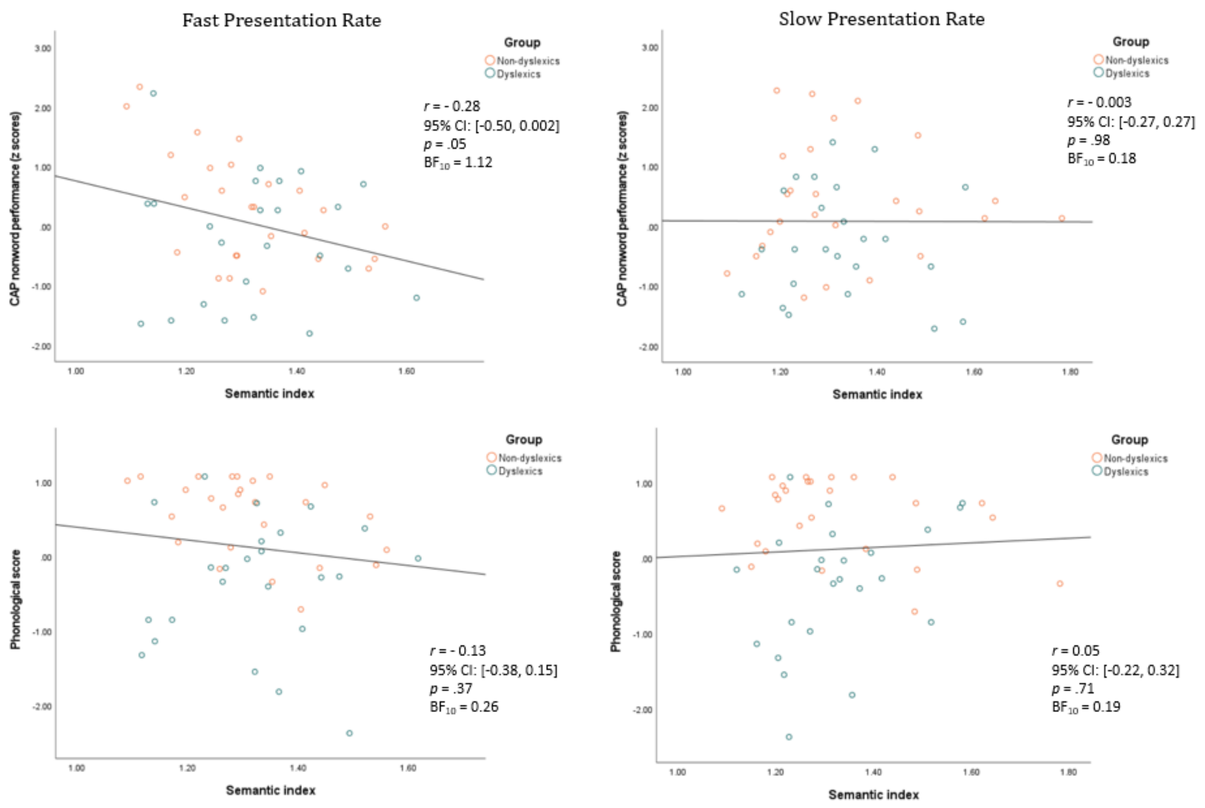

Figure 5.9. *The relationship between phonological scores (y axis), and the semantic index (x axis) in the fast presentation rate ISR task (left panel) and in the sow presentation rate ISR task (right panel).*

Additional analysis: Experiments 1 and 2 comparisons

A final analysis was computed to compare results and magnitude of effects of Experiments 1 and 2. It consisted of mixed ANOVA with three independent variables: task (Experiment 1 imageability vs. Experiment 2 semantic relatedness), presentation rate (fast vs. slow), semantic support (high imageability/semantically related vs. low imageability/semantically unrelated), and group (dyslexics vs. non-dyslexics). Recall was better in Experiment 2, in which semantic relatedness was manipulated (main effects of task, BF_{incl} = $1.65*10^7$), and a more substantial amount of high imageability and semantically related words were recalled in any position than low imageability and unrelated words (main effect of semantic support, $BF_{incl}= \infty$). There were no main effects of group (BF_{10} = 0.53) and presentation rate (BF_{incl} = 0.76). There was an interaction between task and semantic support whereby semantic support improved recall more substantially when semantic relatedness was manipulated than when imageability was manipulated (BF_{incl} = 4.55*10^6, see **Figure 5.10**), and no interaction between semantic support and group (BF_{incl} = 0.26).

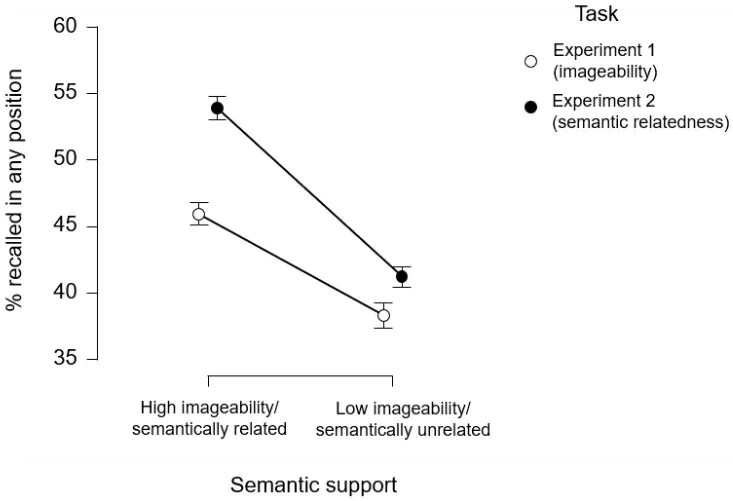

Figure 5.10. *Interaction between task and semantic support for items recalled in any position at the immediate serial recall task.*

Experiment 2: Summary

The aims of Experiment 2 paralleled those of Experiment 1, but with a focus on manipulating semantic relatedness instead of imageability. As observed in Experiment 1, lexical-semantic effects were preserved under speeded encoding conditions; consistent with the idea that LTM effects arise without strategic elaboration (Kowialiewski & Majerus, 2018; Pham & Archibald, 2022a). Finally, the relationship between phonological skills and semantic index – whereby participants with poorer nonword performance show greater benefit of lexical-semantic associations - was not supported with sufficient evidence although there were suggestive indications in the fast presentation rate condition.

5.5 Overall discussion

Manipulations of imageability and semantic relatedness, tested with dyslexic and non-dyslexic individuals in regular immediate serial recall conditions, were compared with those tested under rapid rate (speeded) conditions, to determine whether semantic effects are preserved under speeded conditions, and to examine relative reliance on semantic variables in dyslexic participants. Lexical-semantic effects were consistent across experiments with better recall performance for high compared to low imageability word lists, and for semantically related compared to unrelated word lists, irrespective of presentation rate. Interestingly, the relationship between phonological skills and the magnitude of imageability effects was observed only under fast presentation rates.

An important finding of this study was that imageability effects were maintained at a similar level in a fast-encoding ISR paradigm. This could suggest that long inter-item intervals for rehearsal are not necessary for such an effect to arise (Campoy et al., 2015; Shulman, 1970, 1971; see also Experiment 1 of Souza & Oberauer, 2018). More precisely, while Campoy et al. (2015) found that the imageability effect was amplified by slow presentation rate (1 item per 2 seconds), the present study indicated that the influence of imageability was not moderated by faster presentation rate (i.e., no evidence for an interaction between the effect of imageability and presentation rate), but if anything, it biased a stronger semantic advantage. Order errors, on the other hand, were more frequent in the slow presentation rate than in the fast one, and could be due to increased time for strategic processing like mental imagery, which could lead to reshuffling of item order. However, despite the fast presentation rate with no inter-item gaps reducing the opportunity for participants to strategically encode items, it cannot be firmly asserted that participants did not employ any strategies in the fast condition due to predictable list length and emphasis on item order in the instructions of the ISR tasks, which encourage list and item level elaboration (Morrison et al., 2016). Reconstructive recall processes are predicted by redintegration accounts (Hulme et al., 1991; Lewandowsky, 1999; Schweickert et al., 1999), since the degraded phonological trace would be matched with long-term stored lexical-semantic representations, and the richer the lexical-semantic representation, the better the phonological trace can be retrieved.

In Experiments 2 and 3 of Campoy et al. (2015), the use of a dual task paradigm, in which participants completed an ISR and a visuo-spatial task simultaneously, did not mitigate the imageability effect, suggesting that semantic effects were more likely the result of automatic rather than strategic encoding. Thus, evidence presented here can also be framed around language-based models of vSTM (Acheson & MacDonald, 2009b; Majerus, 2013; N. Martin & Saffran, 1996; Patterson et al., 1994; Schwering & MacDonald, 2020) assuming that interactive interactions between the semantic, lexical, and phonological systems support the phonological trace from encoding, which result in greater support for high-imageability words that benefit from richer semantic features than low imageability, abstract words. This semantic support could occur rapidly due to greater activation of the semantic system that feeds back lower levels (lexical and phonological), occurring without conscious intervention. In addition, the observed decrease in phoneme migrations in lists with high imageability words suggests that the richer semantic features of high-imageability words could offer additional cues or anchors, helping to maintain the consistency of the phonological trace, thereby reducing the likelihood of phoneme migrations, which is a specific prediction of the semantic binding hypothesis (Patterson et al., 1994).

Although here, increased semantic support seemed to operate independently of the rate in which items were presented, imageability effects could still be task dependent. Here, the imageability effect arose in both fast (2 items per second) and standard ‘slow’ (1 item per second) ISR conditions, suggesting that this specific effect does not benefit from long inter-item gaps, but this was nevertheless demonstrated within a structured ISR task. Indeed, when alternatively using a running span task with unpredictable list length, whether with fast presentation rate (2.5 items per second), or with slower presentation rate (1 item/1.5 seconds), Kowialiewski & Majerus (2018) found no effect of imageability; the effect only emerged in standard ISR conditions (1 item/1.5 seconds), but was not examined with faster presentation rate, which the present study intended to do. More specifically, standard ISR tasks necessitate the recollection of order, which may facilitate the application of encoding strategies like rehearsal at both the item and list levels (Morrison et al., 2016). This rehearsal, through repeated item exposure, might stimulate the activation of semantic characteristics that differentiate high and low imageability words. In contrast, during running span procedures, it is necessary to keep updating the memoranda with newly introduced items, which may leave less opportunity for semantic features to be activated, potentially explaining why imageability effects may not emerge in these types of tasks.

However, when items are presented at a standard rate (1 item per second), both running span and immediate serial recall tasks would involve the use of encoding strategies with some overlap. Encoding speed could affect strategy use, since fast presentation rate would not allow for efficient elaboration, by preventing rehearsal and inter-item grouping strategies (Souza & Oberauer, 2018; Tan & Ward, 2008), and this impediment would be amplified by unpredictable list lengths (Cowan et al., 2005). Therefore, fast ISR conditions could reduce the deployment of encoding strategies as a result of short inter-item intervals, and fast running memory span tasks could have a stronger preventive effect due to the updating requirement and unpredictable list lengths. The differences in demand between the two tasks, and by extension in the underlying mechanisms they involve, may thus be the source of these contrasting results.

One reason for using ISR instead of running memory span tasks in the current study, aside from a fast rate ISR condition being omitted from Kowialiewski & Majerus (2018), was to allow for direct comparisons with Savill et al. (2019). This study showed that imageability effects in an ISR task related to relative imageability effects in other language tasks tested, such as speeded reading and repetition, and that these effects related to phonological abilities. In the present study, stronger effects of imageability on recall performance in ISR were again found when phonological abilities - indexed by nonword recall performance - were poorer. These results are compatible with the primary systems hypothesis and interactive accounts of language processing (Patterson et al., 2006; Patterson & Lambon Ralph, 1999; Plaut & Kello, 1999), according to which phonological and semantic systems interact, hence reliance on one primary system (i.e., the semantic system) will interactively depend on support provided by other systems (e.g., the phonological system). Consistent with this prediction, the relationship between phonological and semantic systems was found to be stronger in fast ISR conditions, suggesting that when the phonological system is challenged or stressed – which would occur with fast presentation rate and long list length – lexical-semantic variables can play a relatively stronger role, supporting the weak phonological trace. Such a relationship was not found in the context of semantically related lists (Experiment 2), which may have been due to lower difficulty levels since frequency of the selected words was higher than in Experiment 1 (as shown by higher overall recall performance in Experiment 2).

Similar to results of previous chapters, the impact of lexical-semantic manipulations on recall performance did not vary as a function of group (i.e., dyslexic versus non-dyslexic participants with no significant interaction between list conditions and group).

While a few studies have found stronger reliance on semantic information in children with developmental dyslexia in reading tasks (Betjemann & Keenan, 2008; Hennessey et al., 2012; van der Kleij et al., 2019), such compensatory effects in vSTM cannot be strongly concluded with findings of the present study. It is worth considering the heterogenous profiles of the dyslexic participants, as well as overlapping phonological psychometric performance between the two groups, despite significant difference overall, which may explain similar effects on performance. However, while performance did not differ between groups when recalling words, separate group analyses on nonword recall accuracy confirmed some phonological STM disparities between dyslexic and non-dyslexic participants. This indicates that the provision of lexical-semantic information could potentially have a protective effect on recall performance. This protective effect is made evident by the lack of significant differences between dyslexic and non-dyslexic groups in their recall of both high and low imageability words, which inherently carry such lexical-semantic information. Thus, despite the overall variability in performance and overlapping phonological skills between groups, the presence of lexical-semantic information seems to contribute to a more uniform recall performance across different participant groups.

Regarding semantic relatedness, both dyslexic and non-dyslexic individuals appeared to benefit comparably, and there was no conclusive evidence supporting a correlation with phonological capabilities (specifically nonword recall). Semantically related lists comprised triplets pertaining to different semantic categories or themes. Thus, items within semantically related lists could have been grouped under each of these categories resulting in a chunking effect (G. A. Miller, 1956). Chunking constitutes a strategy for recoding information, improving performance in vSTM tasks. For example, if we consider letter span, we observe that this span increases significantly when letters are combined to form a word that has a representation in long-term memory. Short-term memory span is thus not only defined by the number of elements, but also by the possibility that they offer for semantic organisation. The presence of these groups (or chunks) may be responsible for the recall advantage of semantically related lists, as changes in semantic categories that they cause lead to increased distinctiveness, known to increase recall performance of distinct items (Neath & Nairne, 1995). Semantically related and unrelated lists differed only by the semantic links that exist between the items, suggesting that the intervention of semantic knowledge is responsible for recall improvement, and that semantic information allows for vSTM chunking, which increases memory span for related items in the dyslexic and non-dyslexic groups. Therefore, it could be that, as a result of chunking increasing memory span, the phonological system was not under significant pressure in Experiment 2, which could account for the lack of a marked relationship between phonological skills/dyslexia and the semantic relatedness effect. The possibility to compress information held in vSTM under conceptual categories, such as *colour* for the *red-green-blue* sequence in semantically related lists, is also likely to explain better overall recall performance in Experiment 2 (i.e., semantic relatedness manipulation) compared to Experiment 1 (i.e., imageability manipulation).

To conclude, the present study demonstrated the contribution of semantic information in vSTM, and possible interactions between semantic and phonological primary systems. The effect of lexical-semantic variables, such as imageability or semantic relatedness, benefit recall performance in both standard and fast ISR conditions. In particular, the imageability effect seems to be dependent on task demand but not on long inter-item intervals. Therefore, lexical-semantic effects may not entirely rely on encoding strategies since they arise in fast ISR, reducing controlled encoding processes. A robust relationship between phonological abilities and the imageability effect was found in fast ISR, suggesting that not only primary systems interact, but they also seem to be recruited differentially, with semantic knowledge supporting the phonological system to a greater extent when it is weak and challenged.

Chapter 6.

Does semantic coherence provide a stronger stabilising influence on short-term memory in dyslexia?

Open Science Framework link: https://osf.io/zscbe/

6.1 Abstract

A number of studies have indicated that semantic knowledge can have a significant impact on verbal short-term memory performance. These studies, such as those in the prior chapter, have shown that various factors, such as imageability and the semantic relatedness of words can influence how effectively we are able to store and retrieve information in verbal short-term memory (vSTM). The purpose of this study is to investigate the effects of semantic coherence (i.e., meaning arising over word sequences, without syntactic support) on vSTM recall accuracy and errors in adults with and without dyslexia, and whether the overall changes in phonological stability observed by Savill et al. (2018) were replicated. Participants recalled lists of nonwords mixed with random words or words that formed a semantically coherent sequence in an immediate serial recall task. Results confirmed Savill et al. (2018) findings that semantic coherence benefited verbal short-term memory performance. By providing an overarching meaning across the words mixed with nonwords, long-term stored lexical-semantic representations stabilized the whole phonological trace. The enhanced recall particularly reduced the opportunity for phoneme migration and recombination for both words and the embedded nonwords that lacked their own meaning, in line with the semantic binding hypothesis. However, while dyslexic participants benefited from semantic coherence to recall phonemes in the correct position, it did not impact phoneme migrations and recombinations. Thus, the underlying mechanism of this semantic advantage seemed to differ partially between dyslexic and non-dyslexic adults. Dyslexic participants may use

more reconstructive processes when recalling lists of words and nonwords, allowing them to accurately recall items without impacting phoneme migrations.

6.2 Introduction

So far, the studies of vSTM in this thesis, like the majority of immediate serial recall (ISR) studies before them, have adhered to the ISR convention of presenting lists of words with no overarching structure. Yet, in naturalistic language, meaning arises not just from individual words but, more so, from the context and combinations in which words are encountered. Memory span for sentences is substantially greater than for random words (Baddeley et al., 2009; Brener, 1940; Jefferies, Lambon Ralph, et al., 2004; Meltzer et al., 2016; Pham & Archibald, 2022b), suggesting that semantic and syntactic representations play an important part in verbal short-term memory (vSTM) (Marks & Miller, 1964; G. A. Miller & Selfridge, 1950; William, 1961), typically assessed with immediate serial recall tasks. The theories discussed in this section guide examination of how these semantic and syntactic influences might be at play in mixed lists of words and nonwords in the upcoming study.

Language-based models of vSTM (Acheson & MacDonald, 2009b; MacDonald & Christiansen, 2002; Majerus, 2013; N. Martin & Saffran, 1997; Patterson et al., 1994; Schwering & MacDonald, 2020) view vSTM as arising from the interaction between phonological and semantic representations. Importantly, the type of errors made by patients with semantic dementia (Hodges et al., 1994; Jefferies, Jones, et al., 2004; Knott et al., 1997; Majerus et al., 2007; Patterson et al., 1994) shows that, when recalling semantically degraded words, phonological elements of the words tend to break apart and recombine with other items of the list. These types of errors are also known as phoneme migrations (Hoffman et al., 2009; Jefferies et al., 2008; Patterson et al., 1994). Patterson et al.'s (1994) pattern of errors were interpreted as reflecting the deterioration of semantic knowledge, which, when otherwise preserved, stabilises maintenance of correct phonological configuration in vSTM ('semantic glue'), leading authors to formulate the 'semantic binding hypothesis' (SBH) whereby verbal STM function directly emerges from activation of language and associated long-term representations.

This interactionist view diverges from redintegration accounts (Hulme et al., 1991; Lewandowsky, 1999; Nairne, 1990; Saint-Aubin & Poirier, 1999b; Schweickert, 1993b; Schweickert et al., 1999) in a crucial aspect: the lexical status of items appears to affect the degraded trace and phoneme migrations. In redintegration models, the degradation of the phonological trace is believed to be unaffected by the lexicality. However, the SBH suggests that the lexical-semantic properties of words can influence the state and structure of the phonological trace, potentially shaping how and when phoneme migrations occur. This distinction, as will be shown, has significant implications for the understanding and study of vSTM, particularly in the context of our upcoming research on mixed lists of words and nonwords with varying levels of semantic coherence.

According to the SBH, constraint of the phonological trace arises from the learnt phonological configuration of words through exposure in the phonological system, as well as from the additional co-activation of associated semantic representations that occurs when a word is encountered. The semantic binding account predicts that lexical-semantic support helps bind constituent word phonemes together, leading to relatively more frequent phoneme migration errors for less meaningful words or nonwords, where errors might be expected (e.g., when recall capacity is challenged). However, while studies investigating the effect of lexical-semantic variables on phoneme movements in vSTM tested in language unimpaired participants have demonstrated lexical effects on phoneme errors in line with the SBH, the added effects of semantic variables have been mixed. For example, Jefferies, Frankish, and Lambon Ralph (2006b) examined predictions of the SBH in healthy participants by measuring the rate of phoneme migrations in lists comprising words and nonwords. Nonwords do not benefit from tightly bonded phonemes due to their phonological unfamiliarity and lack of meaning, hence mixing words and nonwords in immediate serial recall lists tends to elicit phoneme migrations errors. Results showed that when nonwords were mixed with high frequency words, their constituent phonemes were less likely to migrate, because phonological coherence of the more accessible/familiar word items diminishes the chance for phonemes of nonwords to migrate and recombine with other phonemes in the lists. However, imageability (a semantic variable) did not seem to have an impact on phonological stability, with phonemes of high and low imageability words equally likely to migrate having controlled for frequency. This, alongside the lack of semantic phoneme binding effects in studies from Chapters 2, 3, and 4, suggests phonological-lexical knowledge indexed by word frequency contributes to vSTM more prominently, and reins in the semantic predictions of the semantic binding hypothesis for language unimpaired.

It may be that the added semantic benefit encapsulated in most of these subtle manipulations are usually too modest to be detected behaviourally. In an attempt to examine semantic effects that may contribute to language maintenance in more meaningful contexts, closer to regular spoken language, Savill et al. (2018) designed an ISR experiment incorporating lists comprising words that form a semantically coherent sequence (e.g., *storm-waves-ship*) which were expected to activate supra-item semantic knowledge in vSTM with inter-item associations, and from overarching meaning/concept providing additional semantic constraint in vSTM. Recall performance improved for lists of semantically coherent lists compared to random words lists in an immediate serial recall task. In lists with either semantically coherent triplets or random words mixed with nonwords (i.e., mixed lists of three words and three nonwords, presented in random positions), semantic coherence seemed to impact the full phonological trace. That is, phonemes forming words as well as nonwords were *more* likely to be recalled in the correct position, and *less* likely to migrate when word items were semantically coherent. Based on language-based models of vSTM such as interactive activation accounts of vSTM (N. Martin & Saffran, 1997), the recall advantage for semantically coherent word lists would stem from activation of shared semantic concept which would be reinforced by interactions and communication between linguistic levels. The reduction of phoneme migrations for nonwords in semantically coherent lists resonate with studies in which patients with semantic dementia produce more phoneme migration errors in ISR for poorly comprehended words (Patterson et al., 1994), which can be readily explained by the SBH, whereby lexical-semantic representations influence phonological stability in vSTM It would be difficult to interpret Savill et al.'s (2018) results purely through a basic redintegration mechanism, since if items were reconstructed at the point of recall based on availability from LTM, nonword performance should not change as a factor of lexical-semantic representations since they do not exist in long-term memory. In other words, semantic manipulations should affect item identity without affecting phoneme order errors, and only for portions of the phonological trace containing familiar items (Gathercole et al., 2001b; Poirier & Saint-Aubin, 1995).

Based on mixed results in the literature (Jefferies, Frankish, & Lambon, 2006; Savill et al., 2018; see also Papagno et al., 2013), the first aim of the present study was to replicate the experiment of Savill et al. (2018; Experiment 2) which examined phonological stability in mixed lists of semantically coherent or random word sequences mixed with nonwords. The manipulation of semantic coherence engenders effects at the supra-item level, with temporary connectivity between concepts corresponding to activations above the lexical level (i.e., coherence offering semantic support more than the sum of its parts). This may provide stronger support in vSTM than unrelated words that were used in previous chapters (except in Experiment 2 of Chapter 5). A key observation then would relate to whether not only word recall is boosted by semantic coherence, but also the nonwords embedded. This would provide further clarification on the theoretical debate about the nature of semantic effects in vSTM (i.e., redintegrative *versus* semantic binding accounts).

The second aim of the present study (and assuming semantic coherence effects were found) was to examine whether patterns of stronger semantic effects extended to phonological difficulties at the level found in adults with developmental dyslexia. In light of results from the previous chapter (Chapter 5), whereby adults with dyslexia seemed to benefit from semantic knowledge stemming from imageability and semantic relatedness, it is possible that semantically coherent lists would increase semantic effects through the activation of conceptual information. In addition, if vSTM correspond to the activation of the linguistic system (N. Martin & Saffran, 1997; Patterson et al., 1994; Romani et al., 2008), as predicted by language-based models of vSTM, stronger effects of semantic variables may be expected for dyslexic participants.

To test this, dyslexic and non-dyslexic adults completed immediate serial recall trials taken from the replication experiment in Savill et al. (2018): Specifically, verbal recall performance was measured for six-item auditorily-presented lists containing three monosyllabic words and three monosyllabic nonwords. In these mixed lists, the sequence of three words either offered a coherent meaning (SEM lists, e.g., *wash, sheets, bed*) or did not (RANDOM lists, e.g., *beat, flag, coin*). The use of the controlled sets of stimuli from Savill et al. (2018) allowed for quantifying immediate serial recall (ISR) performance at a phoneme level (to assess phoneme-binding errors), and for determining whether the observation of a stabilising effect of coherent sequences on surrounding nonword was replicated.

A significant main effect of ISR list condition was expected (i.e., better recall accuracy for SEM than RANDOM) both in the non-dyslexic and in dyslexic group. Based on previous observations of semantic-related reductions in phoneme movement (e.g., Savill et al., 2015; 2017; 2018), one of the aims of this study was to determine whether such a semantic advantage effect relates to reductions in specific errors (i.e., in the semantically coherent lists of words and nonwords, there would be fewer errors where phonemes were out of place and merged with other phonemes, compared to the random lists). Given the assumption of relative phonological weakness in the dyslexic group, behavioural differences were expected to emerge between dyslexic and non-dyslexic participants (but the expected pattern of these differences is somewhat open ended): These could manifest as a main effect of group (poorer recall performance overall in the dyslexic group than the non-dyslexic group; which would likely correspond with poorer digit span performance), but similar relative effects of semantic coherence in the dyslexic group than in the non-dyslexic group, or as a significant interaction between list condition and group (larger list condition effect on recall in the dyslexic group, following increased semantic reliance with decreasing phonological capacity (Savill et al., 2019)).

6.3 Method

Participants

Sixty participants were recruited. However, nine participants failed an attention check (see procedure subsection for more details about the attention check) and were excluded. Thus, 51 participants completed the experiment, including a group of 26 participants with a diagnosis of dyslexia aged 18-48 years (*M* = 28.42, *SD* = 9.08, 22 females), and a group of 25 non-dyslexic participants aged 18-33 years (*M* = 21.32, *SD* = 4.11, 16 females). All participants were native English speakers with no history of neurological disorders. Participants were recruited via the University online recruitment system, Prolific, and the university community, and they gave their written informed consent prior to their inclusion in the study, and received payments or course points for their participation. Participants were required to have Google Chrome installed to access the experiment due to its established stability with the Gorilla platform. The study had been approved by the local ethics committee.

Psychometric measures

A battery of psychometric measures suited to an online testing environment (rapid reading; measures of phonological and semantic capacity; and nonverbal reasoning) were used to assess individual language skills of the participants and verify whether dyslexic participants followed the expected profile of relatively poor phonological and speeded reading performance, but semantic and nonverbal performance similar to non-dyslexic participants. The same tests as those used in Chapters 3 and 4 were used in this study, with the Spoonerism test (Warmington et al., 2013), the Rapid Online Assessment of Reading (ROAR, Yeatman et al., 2021), the Digit Span Task forward and backward (adapted by Phil Dean from M. Turner & Ridsdale, 2004), Warrington's Graded Synonyms (Warrington et al., 1998), and the Matrix Reasoning Item Bank (MaRs-IB, Chierchia et al., 2019).

Bayesian independent t-tests were computed to compare cognitive profiles of the dyslexic and non-dyslexic groups (see **Table 6.1**). As expected, the dyslexic group had poorer overall performance at measures of phonological abilities and working memory relative to the non-dyslexic group (with decisive evidence in favour of a group difference for the spoonerisms task, and moderate evidence in favour of a group difference for the backward digit span task). Also, as expected, the groups did not differ with respect to performance on the MaRs-IB matrix reasoning task and Warrington's graded synonyms task, used to gauge semantic knowledge. However, the evidence in favour of a group difference on the task tested to gauge word and nonword reading abilities (where we would anticipate group differences) was only anecdotal. It should be noted that the ROAR task is a lexical decision task which requires rejection, where participants may be using orthographic strategies and it is not a standardised reading/screening measure, so interpretation of this weak difference ought to proceed with caution (but see Yeatman et al., 2021). Nevertheless, this would imply the dyslexic group recruited for this study are likely to have achieved a reading standard to a reasonably well-compensated level.

Table 6.1. *Descriptive statistics for the psychometric tests and Bayesian t-test comparisons between the dyslexic and the non-dyslexic groups.*

	Dyslexics (n = 26)		Non-dyslexics (n=25)		Bayes factor
	Mean	SD	Mean	SD	BF_{10}
Spoonerisms[a]	7.12	3.39	10.6	1.53	1709.92
ROAR					
RT-Words (ms)	379.23	114.71	336.1	98.74	0.13
RT-Nonwords (ms)	525.23	165.03	441.76	137.82	0.12
ACC-Words[b]	0.95	0.05	0.97	0.04	1.56
ACC-Nonwords[b]	0.83	0.11	0.87	0.09	1.17
Digit Span[c]					
Forward	8.04	2.14	9.24	2.17	2.67
Backward	5.64	2.74	7.24	1.92	5.95
MaRs-IB[b]					
ACC	0.46	0.13	0.51	0.14	0.73
Warrington's graded synonyms[d]					
ACC	28.96	11.44	31.48	7.39	0.4

Note. ACC = Accuracy, RT = Response Time (msec), SD = Standard Deviation. Bayes Factors (BF_{10}) > 3 indicate evidence in favour of a group difference and BF_{10}< 0.3 indicate evidence for the absence of an effect. These values are shown in bold.

[a] *Maximum score = 12*

[b] *Mean accuracy*

[c] *Maximum score forward = 18, and backward = 16*

[d] *Maximum score = 50*

Stimuli

Lists of words and nonwords for use in the ISR task were taken from the replication experiment in Savill et al. (2018). They consisted of 26 lists of semantically coherent monosyllabic words mixed with nonwords (e.g., "chop, /sʌt/, hedge, shears, /θaɪk/, /lɪn/")[10] and 26 lists of random monosyllabic words mixed with nonwords (e.g., "/piːdʒ/, fit, shell, /blɔːʳm/, grave, /næp/") (see Appendix F). Words from semantically coherent lists formed a meaningful, coherent sequence such as "*bold, stunt, leap*", or "*cop, thug, van*". Coherence and ratings were acquired by Savill et al. (2018) and showed that word

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[10] International Phonetic Alphabet notation for nonwords within slashes.

triplets were highly coherent (*M* = 6.15, *SD* = 1.11, on a scale from 1 to 7 with 1 = not coherent and 7 = highly coherent). Each list was six items long with three words and three nonwords mixed in an unpredictable way. Words and nonwords were presented equally in each position, and were not repeated across lists. There were no phoneme repetitions within each list allowing for the tracking of the phoneme migration errors. Lexical frequency and imageability ratings were similar for semantically coherent and random word lists (see **Table 6.2**). Two versions of the ISR task were used, which consisted of the same lists but played in a reversed order. Items were recorded by a female British speaker, and were 750ms long with sound intensity controlled in Praat.

Table 6.2. *Psycholinguistic variables for the semantically coherent and random word items, taken from Savill et al. (2018)*

		SEMANTICALLY COHERENT	RANDOM
Lexical Frequency	*M*	4.47	4.45
	SD	1.52	0.74
Imageability	*M*	5.12	5.16
	SD	1.52	1.28
Grammatical class			
Noun	*%*	85.9	82.05
Verb	*%*	10.26	10.26
Adjective	*%*	3.85	7.69

Note. Lexical frequency is based on values from SUBTLEX-UK (Van Heuven et al., 2014), where 1 indicates the lowest frequency and 7 indicates a higher frequency. Imageability is derived from values in Cortese (2004), with 1 representing the least imageable and 7 signifying the most imageable.

Aside from the list stimuli, an image of a 2.5 cm diameter blue dot was created to be used in the ISR dummy trials used to discourage participants from writing the items and to keep their attention focused on the screen (see procedure subsection for more information about these trials).

Procedure

The experiment was designed and hosted on Gorilla.sc. Participants were required to complete the experiment in a quiet environment, to wear a headset with an integrated microphone, and to use Chrome browser to allow for better stability. Before performing the ISR task, an attention check was presented to the participants. This verified whether participants were attentively reading instructions by asking them to press a key on the keyboard instead of clicking on a “next” button on screen in order to start the experiment.

If participants failed this check, they were excluded from the experiment. If they successfully completed this check, they were presented with instructions for the ISR task.

Participants were notified that they would hear lists of six items comprising words mixed with nonwords. They were instructed to repeat each list in the same order, even if unsure and to try and produce the fullest response possible. In addition, they were advised to keep their hand on the mouse in order to click on a blue dot when they saw it appear on screen. The ISR task started with two practice trials after which the instructions of the task were repeated, and the task started. Items were presented at a rate of one item per second whilst an exclamation point was presented on screen. At the end of the list, a question mark was presented on screen to prompt participants to verbally recall the list. After recalling a list, participants clicked on an arrow on screen to start the next trial. Twenty-six semantically coherent and 26 random lists were presented in a pseudorandom order with a rest break halfway through the task. Throughout the task and amongst these experimental trials, there were three further dummy trials for participants to respond to, which were not subsequently analysed, in which a blue dot appeared at a random location on screen. Responses to experimental trials were digitally recorded and stored on the Gorilla.sc server for later coding. After the ISR task, participants completed standardised psychometric tasks.

The experiment ended with a debrief form that detailed the aims of the experiment and collected information about the environmental conditions in which participants completed the study. Participants were asked if they completed the experiment in a quiet environment, if there were distracted at some point during the experiment, and if they wrote down the to-be-recalled items in the ISR task. The experiment took approximately one hour to complete.

Response coding and analysis

Responses to the ISR task were coded offline, phoneme by phoneme, to allow for analysis at the item level and at the phoneme level, mirroring the method used by Savill et al. (2018). To allow for direct comparison with Savill et al. (2018) results, and to capture errors that might not be necessarily phonologically connected to the intended target, a coding method that focused on responses instead of target-based was employed.

Responses were coded as: 1) recalled in the *correct* serial position (CIP), 2) item order errors for items recalled in the *incorrect* serial position (ORD), 3) CIP and ORD responses constituted the CAP measure which captured items recalled in *any* position, 4) missing responses identified as OMISSIONS if less than six items were recalled, 5) item recombination errors (RECOMB) when the response item consisted of more than on target item in the list, 6) item non-recombinations errors (NON-RECOMB) for partially correct response which did not recombine with another item in the list. The final code was 7) OTHER which corresponded to all other errors that were phonologically unrelated to the target lists such as intrusions (see Appendix G for a worked example coding for a single trial).

Item level response analyses

The first analysis examined the impact of list condition (i.e., semantically coherent vs. random) on recall accuracy and errors. Differing from Savill et al. (2018), analyses were conducted with Bayesian mixed ANOVAs, including group (dyslexic vs. non-dyslexic) as a between-subjects factor. In order to examine the impact of semantic coherence in each group independently, Bayesian paired t-tests were computed for each measure, comparing recall of semantically coherent and random lists.

Phoneme level responses analysis

To see whether there were signs of effects on nonwords as evidence of trace-level effects, second analyses considered phoneme movements split by lexicality. Responses were expressed as a percentage of the total target phonemes. These analyses allowed for the identification of recombination errors.

Phoneme responses split by lexicality were analysed with Bayesian mixed ANOVAs including groups as a between subject factor, before Bayesian paired t-tests were computed in each group to compare the effect of semantic coherence on recall in dyslexic and non-dyslexic groups independently. This allowed to examine the magnitude of semantic coherence effects in each group.

Relationship between phonological skills and the semantic coherence effect

To examine the relationship with phonological abilities and the magnitude of the semantic effect, correlations between participants' phonological scores (derived from the average ROAR nonword accuracy and spoonerisms z scores) and semantic indices corresponding to the ratio between coherent mixed and random mixed scores for the CAP measure at the phoneme and item levels were computed.

6.4 Results

Item level responses

Recall accuracy

There was a substantial effect of semantic coherence on items correctly recalled in *any* position (CAP, see **Figure 6.1** for estimated means). More items were recalled in lists that contained a semantically coherent sequence of words alongside nonwords than in lists that comprised random words and nonwords (BF_{10} = 214208). Groups' performance did not significantly differ (BF_{10} = 0.82 for CAP). There was no group by list condition interaction (BF_{incl} = 0.74).

When recall is analysed using a strict serial recall criterion (i.e., items recalled in the *correct* serial position, CIP), the effect of semantic coherence was also found (BF_{10} = 32395), with an anecdotal effect of group (BF_{10} = 1.03), indicating a tendency for weaker correct serial recall in the dyslexic group, and no group by list condition interaction for this measure (BF_{10} = 0.67).

For items recalled in the incorrect position (ORD), there was anecdotal evidence for an effect of list condition (BF_{10} = 1.06), no group effect (BF_{10} = 0.58) and no group by list condition interaction (BF_{10} = 0.86; see **Figure 6.1**).

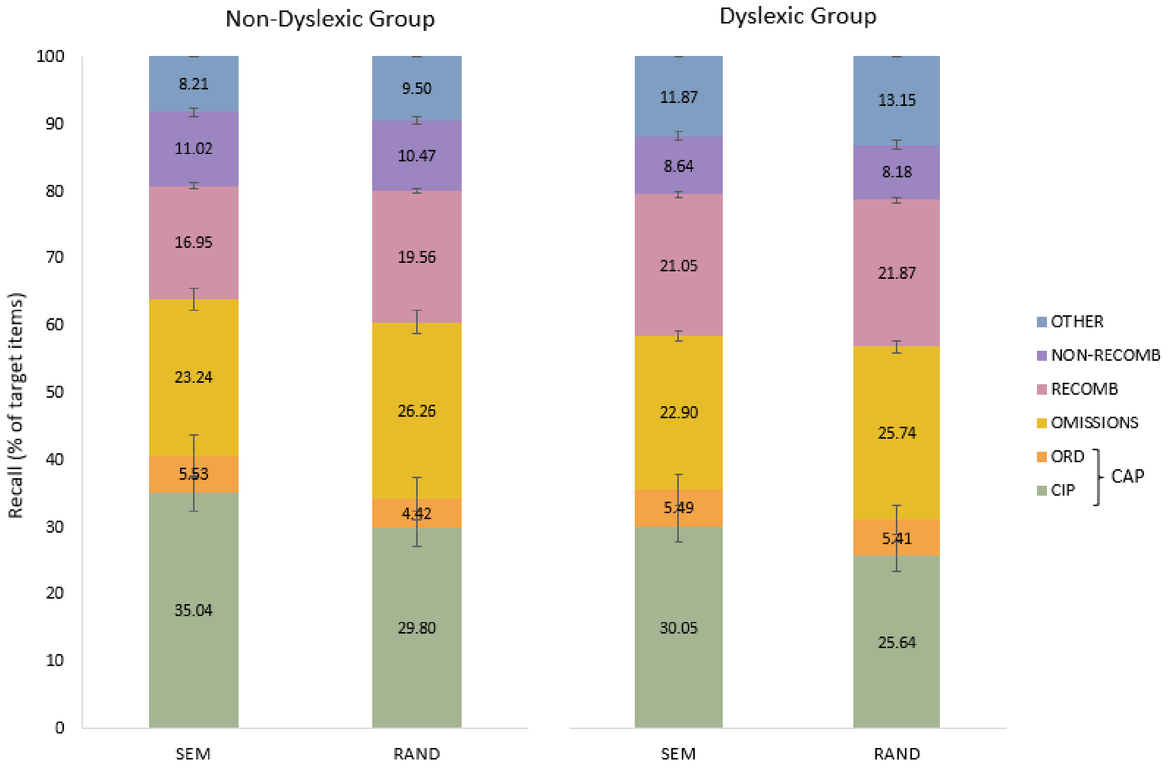

Figure 6.1. *Item-level responses in the non-dyslexic (left panel) and in the dyslexic (right panel) groups. CIP = item recalled in the correct serial position, ORD = item recalled in the incorrect serial position, CAP = item recalled in any position, OMISSIONS = omitted items, RECOMB = recombination errors for responses that recombined with more than one target item, NON-RECOMB = non-recombination errors for responses that did not recombine from more than one target item, OTHER = all other errors.*

Item errors (incorrect responses)

Item omissions were the most common type of error and were more likely in random lists relative to semantically coherent lists (BF_{10} = 192.4). Dyslexic and non-dyslexic participants omitted a comparable number of items (BF_{10} = 0.63), and there was no group by list condition interaction (BF_{incl} = 0.42).

As predicted, phoneme recombination errors were more likely in the random lists than in the semantically coherent lists (BF_{10} = 4.92). Again, there were no effects of group and no group by list condition interaction for this measure (group: BF_{10} = 0.74; group × list condition: BF_{incl} = 0.92).

Like in Savill et al (2018), non-recombination phonological errors were not impacted by semantic coherence (BF_{10} = 0.41). There was weak evidence in favour of a group difference for non-recombination errors whereby non-dyslexic participants produced more of these errors overall than dyslexic participants (BF_{10} = 2.51), but no group by list condition interaction (BF_{incl} = 0.25)

Independent analyses of item accuracy and errors by groups

Independent analyses of recall performance split by groups revealed that both the dyslexic and the non-dyslexic groups benefited from semantic coherence on recall performance. Although Bayes values did not significantly differ between groups, in terms of a null interaction, the dyslexic group had a larger Bayes value for the effect of semantic coherence on recall accuracy than non-dyslexic participants (see **Table 6.3**, CAP and CIP). Although there was no interaction in the omnibus analyses, semantic coherence significantly affected recombination errors in the non-dyslexic group only, with more errors in random lists relative to semantically coherent lists. Both groups were similarly impacted by list condition for omissions, with more omissions in random lists than in semantically coherent lists. Non-recombination errors and order errors were not impacted by list condition in either group.

Table 6.3. *Bayesian t-test comparisons showing BF_{10} values in the dyslexic and non-dyslexic groups*

Group	ISR response: SEM vs. RAND lists						
	CAP	CIP	ORD	OMISSIONS	RECOMB	NON-RECOMB	OTHER
Non-dyslexic	**270.92**	**41.07**	1.76	**6.84**	**5.63**	0.29	0.92
Dyslexic	**439.36**	**734.64**	0.22	**6.08**	0.32	0.32	1.42

Note. BF_{10} values for items recalled in any position (CAP), which comprises items recalled in the correct (CIP) and incorrect serial position (ORD). RECOMB = responses recombining target phonemes from more than one item. NON-RECOMB = phonologically related errors that did not recombine from more than one target item. BF_{10} values > 3 are shown in bold.

Phoneme level responses split by lexicality

Word phonemes

Bayesian mixed ANOVA

Word's phonemes were more likely to be recalled in any position (CAP) in semantically coherent lists than in random lists (SEM: *M* = 57.29%, *SD* = 14.24%; RAND:

M = 49.9%, *SD* = 12.77%; CAP: BF_{10} = 1.37*10^6). There was no between group difference (BF_{10} = 0.99), and no group by condition interaction (BF_{10} = 0.74).

When recall was analysed using a strict serial recall criterion (i.e., phonemes recalled as part of a correct item in the correct position, CIP), phonemes CIP were more likely when words were semantically coherent (SEM: *M* = 49.84%, *SD* = 14.6%; RAND: *M* = 43.69%, *SD* = 11.76%; CIP: BF_{10} = 352386). There was anecdotal evidence in favour of a group difference (non-dyslexic group: *M* = 49.94%, *SD* = 14.63%; dyslexic group: *M* = 43.34%, *SD* = 10.66%; BF_{10} = 1.3), and no evidence in favour of an interaction between group and list condition (BF_{incl} = 0.7).

There was a tendency for word phonemes to be produced as part of an item order error (ORD) at a higher rate in semantically coherent lists (*M* = 7.45%, *SD* = 6.34%); than in random lists (*M* = 6.21%, *SD* = 7.04%; ORD: BF_{10} = 2.44), but no group difference (BF_{10} = 0.52), and no interaction for this measure (BF_{incl} = 0.6).

Phoneme recombination errors (i.e., phoneme migrations) were more likely in random lists (*M* = 18.21%, *SD* = 7.47%) relative to semantically coherent lists (*M* = 16.26%, *SD* = 8.06%; RECOMB: BF_{10} = 7.69). There was weak evidence for a group difference with slightly more recombinations produced in the dyslexic group (non-dyslexic group: *M* = 15.24%, *SD* = 7.1%; dyslexic group: *M* = 19.39%, *SD* = 8%; BF_{10} = 1.88), and no group by list condition interaction (BF_{incl} = 0.92).

Non-recombination errors (i.e., a partially correct item that contained only phonemes from one target) accounted for only 4.3% (*SD* = 2.15%) of the responses produced and were not affected by list condition (NON-RECOMB: BF_{10} = 0.94). Non-dyslexic participants produced more non-recombination errors than dyslexic participants (non-dyslexic group: *M* = 4.95%, *SD* = 2.29%; dyslexic group: *M* = 3.6%, *SD* = 1.79%; BF_{10} = 6.13), and there was no group by list condition interaction (BF_{incl} = 0.19).

Bayesian paired samples t-test comparisons split by group

As can be seen in **Figure 6.2**, the effect of semantic coherence on phonemes recalled in any position (CAP) was observed in the non-dyslexic group (BF_{10} = 809.06), and in the dyslexic group (BF_{10} = 602.89). A beneficial impact of semantic coherence on word phonemes recalled as part of a correct item (CIP) was observed both in the non-dyslexic group (BF_{10} =131.94), and in the dyslexic group (BF_{10} = 1021.88). Note that the effect of semantic coherence was stronger in the dyslexic group relative to the non-dyslexic group.

Phonemes that formed an item order error (i.e., ORD) were impacted by list condition in the non-dyslexic group only (BF_{10} = 4.81), these errors were more likely to be produced in semantically coherent lists relative to random lists. Phoneme ORD errors were not affected by list condition in the dyslexic group (BF_{10} = 0.24).

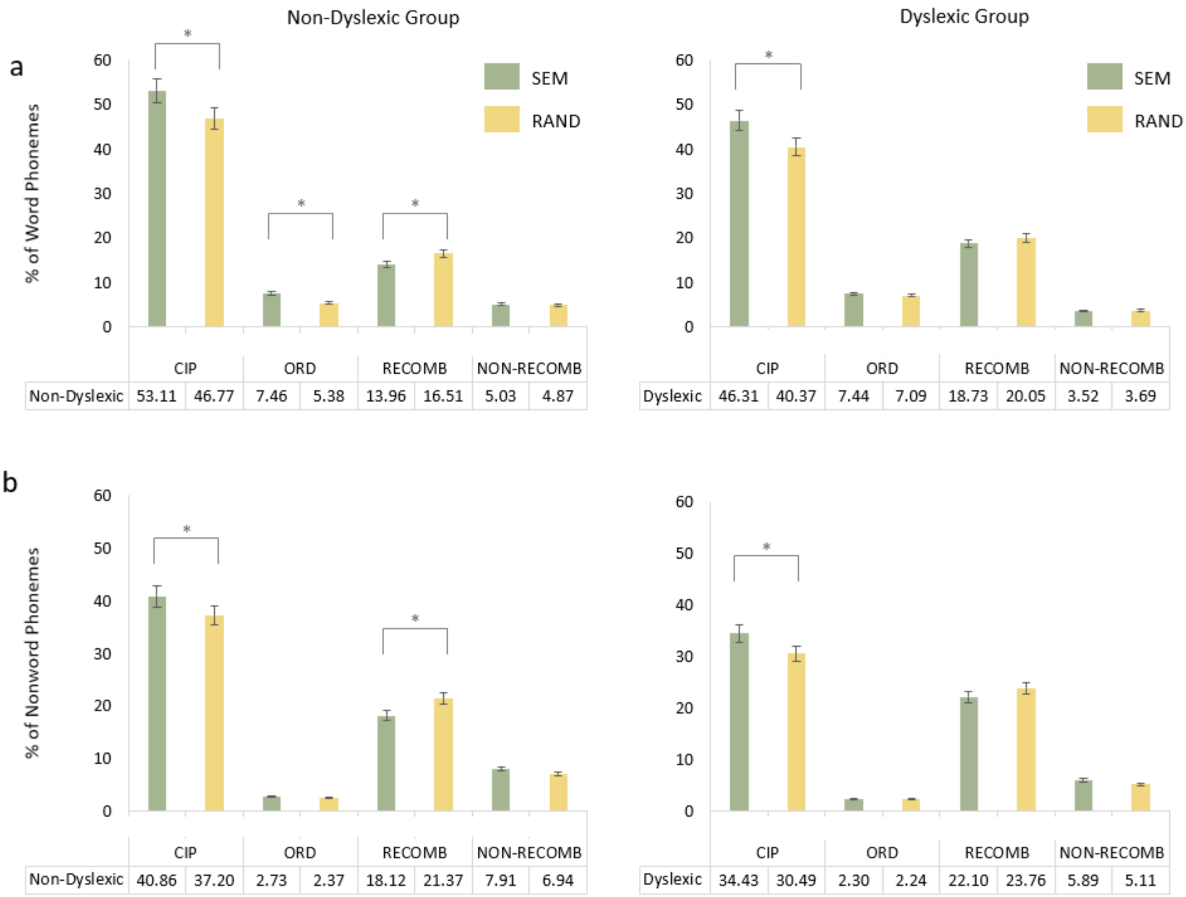

Figure 6.2. *Phoneme level responses for word phonemes (panel a), and nonword phonemes (panel b), split by group with non-dyslexic participants' responses on the left panel and dyslexic participants' responses on the right. Responses are expressed as a percentage of total word and nonword target phonemes. The results of Bayesian t-test comparisons between semantically coherent (SEM) and random lists (RAND) are depicted with a bar when* $BF_{10} > 3$. *CIP = phonemes recalled within items recalled in the correct serial position, ORD = phonemes produced within item order errors, RECOM = phoneme produced as part of a recombination responses with phonemes from more than one target, NON-RECOM = phonemes produced within a response that did not include phonemes from more than one item.*

Word phonemes were more likely to recombine with phonemes from more than one target (i.e., RECOMB) in random lists in the non-dyslexic group (BF_{10} = 4.19). In the dyslexic group, word phoneme recombinations errors were not impacted by list condition (BF_{10} = 0.52). Word phoneme non-recombinations were not impacted by list condition in the non-dyslexic group (BF_{10} = 0.22), and in the non-dyslexic groups (BF_{10} = 0.23).

Nonword phonemes

Bayesian mixed ANOVA

Nonword phonemes were more likely to be recalled in any position (CAP) in semantically coherent lists (SEM: *M* = 40.29%, *SD* = 13.03%; RAND: *M* = 36.28%, *SD* = 11.88%; CAP: BF_{10} = 433.44). There was anecdotal evidence for a between group difference (BF_{10} = 1.71) in terms of fewer nonwords phonemes recalled by dyslexic participants on average (non-dyslexic group: *M* = 41.58%, *SD* = 13.94%; dyslexic group: *M* = 34.73%, *SD* = 9.65%), and no interaction between group and list condition (BF_{10} = 0.84).

When recall was analysed using a strict serial recall criterion (i.e., phonemes recalled as part of a correct item in the correct position, CIP), phonemes CIP were more likely in semantically coherent lists compared to random lists (SEM: *M* = 37.77%, *SD* = 12.78%; RAND: *M* = 33.97%, *SD* = 11.53%; BF_{10} = 379.84). There was anecdotal evidence for a group difference for CIP (BF_{10} = 1.73) and no group by list condition interaction (BF_{10} = 0.7).

An effect of semantic coherence on nonword phoneme recombinations was observed. In semantically coherent lists, nonword phonemes were less prone to recombination compared to in random lists (SEM: *M* = 20.03%, *SD* = 9.24%; RAND: *M* = 22.52%, *SD* = 9.66%; BF_{10} = 15.48). Non-dyslexic and dyslexic participants produced the same proportion of phoneme recombinations (BF_{10} = 0.74), and there was no group by list condition interaction (BF_{incl} = 0.78). There was no effect of semantic coherence on nonword phonemes part of an item order error (ORD: BF_{10} = 0.3), no effect of group (BF_{10} = 0.48), and no group by list condition interaction (BF_{incl} = 0.08).

Nonword non-recombination phonological errors were only anecdotally affected by list condition (BF_{10} = 1.09). Dyslexic participants produced fewer non-recombination errors than non-dyslexic participants (BF_{10} = 3.17), and there was no group by list condition interaction (BF_{incl} = 0.44).

Bayesian paired samples t-tests comparisons split by group

There was strong evidence in favour of an effect of semantic coherence on phonemes recalled in any position (CAP) in the non-dyslexic (BF_{10} = 10.05) and in the dyslexic group (BF_{10} = 9.26, see **Figure 6.2**). More nonword phonemes from semantically coherent lists were recalled as part of a correct item (CIP) in the dyslexic (BF_{10} = 18.61), and in the non-dyslexic group (BF_{10} = 5.42) compared to random lists. Again, note that this effect was stronger in the dyslexic group.

Nonword phoneme recombinations were less likely in the semantically coherent lists compared to random lists in the non-dyslexic group only (BF_{10} = 4.7). There was no effect of semantic coherence on phoneme recombinations in the dyslexic group (BF_{10} = 0.78).

In the non-dyslexic group, ORD (BF_{10} = 0.3), and phoneme non-recombinations (BF_{10} = 0.48) were not impacted by semantic coherence. Similarly, in the dyslexic group, there was no effect of list condition on phoneme ORD (BF_{10} = 0.21), and phoneme non-recombinations (BF_{10} = 0.51).

Relationship between phonological skills and the semantic coherence effect

There was no evidence in favour of a relationship between phonological scores and semantic index for words (r = 0.2, BF_{10} = 0.46), and for nonwords (r = 0.06, BF_{10} = 0.19) at the phoneme level. At the item level, there was weak evidence in favour if a relationship between phonological skills and semantic effect, whereby participants with better phonological abilities show more substantial effects of semantic coherence (r = 0.33, BF_{10} = 2.62).

6.5 Discussion

This study examined whether stronger semantic effects on vSTM recall accuracy and errors were found in adults with dyslexia, and whether relative changes in phonological stability (recall assessed at the phoneme-level) found in Savill et al. (2018) were replicated. Key findings were as follows:

(1) Results from Savill et al. (2018) were fully replicated online, both at the item and phoneme levels. Semantic knowledge stabilised phoneme order both for words and meaningless nonwords. In semantically coherent lists, phonemes were less prone to recombine with phonemes from other items, in line with the semantic binding hypothesis.

(2) Despite the lack of interaction between group and semantic effects, independent analyses revealed differential impacts of semantic knowledge on recall amongst the groups. Semantic knowledge affected recall accuracy and phoneme migrations in the non-dyslexic group, whereas in the dyslexic group, semantic factors influenced the frequency in which items and phonemes were recalled in the correct serial position (i.e., recall accuracy) but did not affect recombination errors.

(3) Bayes values indicated more substantial semantic coherence effects in the dyslexic group relative to the non-dyslexic group for items recalled in the correct serial position. However, this difference did not manifest as a significant interaction.

These will now be discussed in turn.

Support for an effect of semantic coherence of items on word and nonword recall in verbal short-term memory

The impact of semantic coherence of word items on nonwords demonstrated that the constraining influence of such a variable can extend to unrelated, meaningless nonwords which do not enjoy lexical-semantic representations. These observations replicate the findings of Savill et al. (2018), and are in line with semantic coherence supporting of the entire phonological trace in verbal short-term memory (vSTM), as suggested by the semantic binding hypothesis (Patterson et al., 1994). That is, lexical-semantic binding strengthens the likelihood of phonemes being recalled in the correct serial position, with phonemes in a sequence mutually reinforcing each other's activation such that words with richer semantic representations, such as those found in semantically coherent lists, would provide stronger phoneme binding giving reduced opportunity for nonword phonemes to be recalled out of sequence than with words with poorer semantic representations, like those found in random lists. Contrastingly, redintegration accounts (Hulme et al., 1991, 1997; Schweickert, 1993b), which are based on the premise that degraded phonological traces in vSTM are reconstructed by comparing them with potential lexical candidates and using long-term stored knowledge, would struggle to explain how nonwords (lacking the lexical-semantic representations of words) would benefit from a semantic coherence manipulation.

In the present study, participants may have noticed word sequences and used this as an encoding or retrieval cue to strategically reconstruct responses, but recombination error effects and phoneme effects on nonwords would not be readily accounted for by this. The semantic binding hypothesis's proposition of an interactive relationship between semantic and phonological representations accommodates even nonword recall being influenced, when presented in a semantic context supporting the phonological trace in vSTM. An alternate or complementary interpretation of the influence of semantic coherence on nonword recall hinges on the facilitative role of semantic support. Specifically, lists that carry higher degrees of semantic coherence could render the words within them more memorable, thereby streamlining the recall process. This, in turn, would free up cognitive resources, allowing participants to direct more focused attention towards the accurate recall of nonwords.

Word’s phonemes from semantically coherent lists were less likely to migrate than word’s phonemes in random lists. This finding is consistent with Savill et al. (2018) results, however, when using imageability as a semantic variable in mixed lists, Jefferies, Frankish, and Lambon (2006) found an effect of imageability on the stability of nonwords, but not on words. In the present study (and in Savill et al., 2018), words in semantically coherent lists benefited from an overarching meaning that allowed for inter-item associations. Based on interactive activation models (Dell et al., 1997; McClelland & Rumelhart, 1981), words from semantically coherent lists were more likely to share a common semantic node (e.g., ‘live’, ‘band’, ‘stage’ that could be grouped under ‘concert’ semantic category), consequently, these words could reactivate each other through the lexical and semantic nodes which would reinforce their activation levels, making them more likely to be correctly recalled in vSTM. In addition, due to the story-like nature of the stimuli used in this study, participants may have formed sentences with the presented words as a strategy to remember them. Substantial recall advantage for sentences over individual words has been observed in a myriad of studies (e.g., Brener, 1940; Miller & Selfridge, 1950; see also Marks & Miller, 1964; William, 1961), and seems to be due to additional information provided by grammar and syntactic besides phonological and semantic) representations in sentence contexts.

Does semantic coherence affect verbal-short term memory similarly in dyslexic adults?

The observed effect of semantic coherence on recall accuracy, which encompasses items recalled in their correct serial order, was present in both dyslexic and non-dyslexic adults. Despite the lack of interaction between semantic effects and groups, independent analyses of the effect of semantic coherence on recall accuracy in dyslexics and non-dyslexics showed that the effect of semantic coherence was more substantial in the dyslexic group. Findings from this study and Chapter 5 (Experiment 1) converge on the implication of semantic information acting as a useful prop for individuals with dyslexia, particularly in tasks where phonological skills are essential.

These findings fit with hypotheses envisaging dynamic interactions between phonological and semantic systems, such that use of one primary system (e.g., the semantic system) will depend on support provided by other systems (e.g., the phonological system) (Patterson & Lambon Ralph, 1999; Plaut, 1997; Seidenberg & McClelland, 1989). Indeed, in Chapter 5, stronger effects of imageability on recall performance in ISR were found when phonological skills were poorer. Furthermore, the relationship between phonological and semantic systems was found to be stronger in fast ISR conditions, suggesting that lexical-semantic variables play a more significant role when the phonological system is challenged or stressed. Taken together, these findings indicate that individuals with dyslexia may harness semantic knowledge (from words they know well) to compensate for their weaker phonological abilities, particularly in challenging conditions that stress the phonological system. However, the extent of this compensation and its broader applicability in various tasks require further investigation.

Despite the lack of significant interaction, it is worth noting observed differences in how this semantic coherence influences different aspects of recall in dyslexic and non-dyslexic individuals. Unlike non-dyslexic individuals, the rate of phoneme recombination errors, also known as phoneme migrations, amongst dyslexic individuals remained unaffected by semantic coherence. This pattern might suggest that the positive effect of semantic coherence on recall for dyslexic individuals might relate more to use of strategic and reconstructive recall processes than effects on additional stabilisation of the phonological trace, compared to semantic effects for their non-dyslexic counterparts: strategic selection of lexical-semantic candidates to support recall performance would conceivably influence the likelihood of correctly recalling words, but not necessarily the relative incidence of phoneme migrations. However, strategic reconstruction would be unlikely to be the only mechanism in operation, as the structure of the lists presented was unpredictable. That is, uncertainty in the position of words and nonwords in a sequence makes the use of strategic reconstruction less probable, as it relies on knowledge of items' lexical status (Jefferies, Frankish, et al., 2009).

The observation that dyslexic adults demonstrate an effect of semantic coherence in mixed lists of words and nonwords on the recall of phonemes in the correct position, but not on phoneme migrations, could also be explained by dyslexic individuals' underlying phonological difficulties, which might still lead to a relatively high rate of phoneme migration errors. These phonological difficulties are a key characteristic of dyslexia and could persist regardless of the semantic properties of the list. Therefore, while semantic coherence may aid dyslexic individuals in recalling phonemes in the correct order, their persistent phonological processing challenges may continue to result in a lack of improvement in phoneme migrations.

Conclusions

Overall, this online study replicated lab-based findings of Savill et al. (2018), which demonstrated that semantic coherence, providing an overarching meaning to mixed lists of words and nonwords, improves performance in verbal short-term memory. In doing so, long-term stored lexical-semantic representations, that are part of the language system, seem to help stabilising the phonological trace by increasing the likelihood to correctly recall words and nonwords, and by reducing the opportunity for word and nonword phoneme to migrate and recombine with other phonemes of the list, in line with the semantic binding hypothesis. It seems that the underlying mechanism of this semantic advantage partly differs between dyslexic and non-dyslexic adults, with dyslexic participants possibly using more reconstructive processes when recalling lists of words and nonwords, allowing them to accurately recall items, but without impacting phoneme migrations. Thus, if the semantic binding hypothesis seems to be best suited to the overall results of this study, it is undeniable that more strategic redintegration may occur in vSTM, particularly for dyslexic adults.

Chapter 7. General discussion

7.1 Introduction

In the theoretical introduction to this work, I outlined viewpoints suggesting that the retention of information in vSTM relies not only on phonological coding, but also on semantic information stored in long-term memory (LTM). Numerous studies have supported the idea that LTM, particularly semantic knowledge, has an impact on short-term recall. However, it is only in relatively recent years that the contribution of semantic information has received due attention, as earlier research, such as Baddeley's seminal work (Baddeley, 1966, 1986; Baddeley & Hitch, 1974) and his working memory model heavily emphasised the role of phonological coding in the temporary maintenance of verbal information. Nonetheless, contemporary scientific consensus recognises the effect of semantic knowledge on short-term recall. Modern models of vSTM now incorporate this effect, although they diverge in several aspects, including assumptions regarding the existence of a phonological short-term store that is separate from long-term language systems (Baddeley, 2000; Hulme et al., 1991, 1997). Other views consider that vSTM involves the temporary activation of long-term memory (Acheson & MacDonald, 2009a; N. Martin & Saffran, 1997; Patterson et al., 1994; Schwering & MacDonald, 2020). These language-based models, and the semantic binding hypothesis in particular (Jefferies, Frankish, & Lambon Ralph, 2006b; Patterson et al., 1994), suggest that interactions between semantic and phonological representations play a crucial role in vSTM, and these ideas led to many of the questions explored in this thesis.

Similar to language-based explanations of STM, primary systems accounts of language impairments in neuropsychological populations (Patterson & Lambon Ralph, 1999), envision patterns of language function across tasks arising via interactions between visual, phonological, and semantic representations. These accounts suggest that in situations where phonological representations are weak, such as for individuals with neural damage causing phonological deficits, interactions with semantic representations becomes crucial and support language processing. Analogous to the more dramatic phonological deficits associated with acquired dyslexia, evidence for similar relationships have been observed in individuals with developmental dyslexia experiencing phonological difficulties. These individuals, as indicated in studies like Hennessey et al., (2012), have been observed to demonstrate relatively more pronounced impacts of semantic manipulations on single word reading. Such observations indicate that even individuals with relatively milder phonological weaknesses might compensate their phonological difficulties by relying more heavily on word meanings for language processing. However, a key question that emerges from this observation is whether these compensatory patterns extend beyond the context of reading, as might be predicted by views such as the primary systems hypothesis.

Both primary systems hypothesis (PHS) and language-based models (LB) highlight the interplay between semantic and phonological systems in reading (PSH) and vSTM (LB). However, to the best of my knowledge and prior to the work presented in this thesis, no research had been undertaken to draw these views together to specifically investigate lexical-semantic influences on vSTM in individuals with developmental dyslexia. This research gap highlighted the need to explore how individuals with dyslexia may or may not utilise long-term lexical-semantic information to compensate for their phonological difficulties that affects vSTM. The data collected during this research contributed to specifying the effects of different types of lexical-semantic knowledge on short-term recall, thereby attempting to unify predictions of language-based accounts of vSTM and the primary systems hypothesis, and providing valuable insights to address the questions raised by the discrepancies between existing models. In this final chapter, I will begin by summarising key findings from the collected data, followed by an analysis of how these findings contribute to broader theoretical considerations.

7.2 Summary of key experimental findings

The first experiments presented in Chapter 2 and 3 examined whether effects observed from meticulously controlled training manipulations could be consistently replicated and further extended. I specifically examined the effect of newly acquired linguistic knowledge and semantic representations on vSTM, and their implications for individuals with dyslexia. In Chapter 2, the study aimed to replicate and extend Savill et al.'s (2017) study investigating whether new lexical and semantic information independently contribute to phonological processing in vSTM and determine if dyslexic individuals benefit more from that semantic support than non-dyslexic participants. Results showed that new phonological-lexical representations acquired via previous exposure improved overall recall of those nonword forms, but there was no additional benefit from having semantic associations. Moreover, the electrophysiological measure, used to capture implicit phonological familiarity, only differentiated between semantically trained and phonologically familiarised nonwords in non-dyslexic participants. These findings suggest that phonological representations assist in maintaining new phonological forms in vSTM, while rapid learning may be insufficient for the establishment of semantic representations. Perhaps lexical-semantic associations develop more slowly for dyslexic individuals.

Chapter 3 addressed methodological concerns from the previous chapter by improving the training of nonwords and associated semantic features by increasing exposure, including a repetition task, and reducing overall learning burden. The recall advantage for phonologically familiarised nonwords was replicated, but an additional advantage was observed for the semantically trained nonwords compared to phonologically familiarised nonwords. Dyslexic and non-dyslexic participants performed similarly and benefited from semantic associations to a similar extent. This advantage was observed at the item level without differentially affecting phoneme migrations. These results support the likely interpretation that long-term linguistic knowledge including available semantic knowledge, along with redintegrative processes during recall, contribute to vSTM.

In Chapter 4, a novel approach was taken to investigate the effect of long-term linguistic representations on vSTM. This was done by associating nonwords with high or low imageability words. The idea behind this strategy was to extend the imageability advantages of the associated words to the nonwords, while also controlling for the contribution of phonological familiarity and frequency of exposure. While recall performance again showed the advantage of phonological familiarity of items, relative to untrained nonwords, it did not differ as a function of association with a low or high imageability word. Methodological limitations, such as the choice and written presentation of high imageability words, competition with preexisting word presentations and/or insufficient training may explain this result.

Collectively, the studies using trained nonwords indicate that dyslexic individuals similarly utilise word knowledge within STM, and access to these representations may be similarly enhanced by the association with semantic information. However, these effects tested following a short training period may not capture differences in long-term activation typical of long acquired words, and warrant further exploration.

In Chapter 5, the focus shifted from the word learning approach to examining the influence of well-integrated lexical-semantic representations in vSTM. The primary objective was to explore how factors such as imageability and semantic relatedness affect vSTM performance in relation to phonological skill, with presentation rate added as an additional variable for consideration. This study compared regular and speeded immediate serial recall (ISR) conditions in both dyslexic and non-dyslexic individuals, testing imageability and semantic relatedness list manipulations. The results of Chapter 5 revealed consistent lexical-semantic effects across experiments between groups, irrespective of presentation rate. High imageability word lists and semantically related word lists were recalled more accurately compared to low imageability and unrelated word lists, respectively. The manipulation of imageability was also found to influence phoneme-level responses by constraining phoneme migrations (N.B. equivalent analyses were not possible to assess this for semantic relatedness). Interestingly, these semantic effects were similar in magnitude for dyslexic and non-dyslexic participants. However, the relationship between nonword performance and the imageability effect showed that when the presentation rate was faster, the imageability effect was larger in individuals with weaker phonological capacity (i.e., in participants largely represented by the dyslexic participants). The findings of this study show that semantic knowledge effects, such as imageability, are not solely dependent on slow presentation, and the fast effects found suggest the support from these semantic variables is unlikely to be reliant on strategic recall processes, supporting language-based accounts of vSTM.

Moving to Chapter 6, the study focused on exploring the effects of semantic coherence (i.e., telegraphic sentence-like sequences) on vSTM recall accuracy and errors in adults with and without dyslexia. This study aimed to replicate and extend Savill et al.'s

(2018) findings to a cohort of dyslexic participants, to determine whether semantic coherence enhances vSTM performance and impacts phonological stability. Participants were presented with lists of nonwords mixed with either random words or words that formed a semantically coherent sequence in an immediate serial recall task. Across participants, the results of Chapter 6 confirmed the earlier findings, demonstrating that semantic coherence significantly improved vSTM performance. By providing an overarching meaning to mixed lists of words and nonwords, long-term lexical-semantic representations stabilised the entire phonological trace, not just for words but also significantly for nonwords. This stabilisation reduced the opportunity for phoneme recombinations, aligning with the semantic binding hypothesis. Notably, the pattern of errors indicated that the underlying mechanism of this semantic advantage could differ between dyslexic and non-dyslexic adults. In the case of dyslexic participants, semantic coherence did not appear to influence phoneme migrations. Despite this, they were still able to accurately recall items, which suggests that a different strategy might have been employed. They may thus rely more upon reconstructive processes when recalling lists of words and nonwords, allowing for accurate item recall without impacting phoneme migrations.

The collective findings from these chapters consistently demonstrate the crucial role of phonological-lexical representations in supporting recall in vSTM. The availability of phonological-lexical information enhances the encoding and maintenance of novel phonological forms, leading to improved recall performance. While studies involving a novel word learning paradigm showed limited evidence for semantic support in vSTM, established semantic knowledge such as imageability, semantic associations, and semantic coherence provided strong support for the influence of semantic representations on vSTM. In light of the objectives of the thesis outlined in Chapter 1, I will first consider the ways in which these findings contribute to our understanding of the contributions of long-term linguistic knowledge on vSTM. I will also analyse the presence or absence of semantic compensation in dyslexia, and attempt to integrate the findings of this thesis within neurobiological perspectives. I will then make recommendations for future research and offer an overall conclusion of the thesis.

7.3 Support for phonological-lexical effects in verbal short-term memory

Across Chapters 2, 3 and 4, strong phonological-lexical effects from nonword exposure on recall accuracy were found, echoing previous studies (Savill et al., 2015, 2017). The approach adopted in Chapters 2 and 3 involved associating nonwords with either blurred images (phonological-lexical condition) or with images of rare objects accompanied by their descriptions (semantic condition). This methodology facilitated an examination of the independent contribution of phonological-lexical knowledge by controlling for individual prior word experiences, underscoring its consistent role in vSTM. In Chapter 4, nonwords were paired with high and low imageability words. The improved performance at the phoneme and item levels for phonologically familiarised nonwords over entirely new nonwords, demonstrate the significant contribution of linguistic knowledge in vSTM. Information about phoneme sequences that has been learnt through a limited number of presentations over the course of training tasks appear to enhance the cohesion of nonwords' constituent phonemes in vSTM. This phonological-lexical effect cannot be accounted for by other linguistic variables such as phonological probability and frequency that could guide recall, since the designed nonwords were controlled for these variables. Supporting these behavioural results, electrophysiological findings from Chapter 2 indicated an enhancement in mismatch negativity (MMN) responses elicited by familiarised nonwords, indicative of improved auditory discrimination of phonological contrasts. These results further substantiate that vSTM is closely intertwined with long-term stored phonological and lexical knowledge.

These findings align well with theories that posit the involvement of the language system in maintenance of vSTM, specifically the semantic binding hypothesis (Patterson et al., 1994). This is particularly evident considering the influence of phonological-lexical knowledge on phoneme migrations. The familiarisation stage might play a crucial role in fostering pattern completion, allowing the correct sequencing of phonemes to be recalled in ISR. This is achieved through the phonological-lexical system, which is capable of anticipating the phoneme sequences of familiarised nonwords, but not of unfamiliar ones (because they do not benefit from long-term representations). An additional boost from semantic knowledge, above and beyond phonological-lexical factors, was found in

Chapters 3, 5, and 6, providing further evidence for language-based models of vSTM (Acheson, Hamidi, et al., 2011; Patterson et al., 1994). The following section (7.4) will provide a thorough examination of the theoretical implications associated with the contributions of semantic knowledge to vSTM.

Based on the findings from Chapters 2, 3, and 4 – and comparable word advantages over unfamiliar nonwords irrespective of semantic status in Chapters 5 and 6 - it is evident that phonological-lexical effects are similarly effective for individuals with dyslexia. Phonological familiarisation was found to be highly beneficial in terms of improving recall performance across both groups, as reflected in an increased recall of familiarised items in both their correct and any positions. While dyslexic individuals typically face challenges with tasks involving phonological processing, these studies demonstrated that they too could effectively utilise newly acquired phonological-lexical knowledge to enhance their recall performance.

However, it is worth noting that phonological familiarisation exhibited a varying degree of influence on the two groups. Particularly, the non-dyslexic group appeared to benefit more from the phonological training, showing less propensity for order errors and phoneme migrations post-training. In contrast, the dyslexic group, despite showing improvement in recall performance, did not exhibit the same extent of reduction in phoneme migrations. In other words, phonological familiarisation appeared to be more effective at reducing phoneme migrations and order errors in non-dyslexic participants compared to dyslexic participants. This suggests that while phonological-lexical representations can support recall performance in dyslexic individuals, they may still struggle more than their non-dyslexic counterparts with maintaining the precise order of information, particularly at the phoneme level (Majerus & Cowan, 2016). However, these differences did not consistently appear throughout all chapters and failed to manifest as significant interactions. They were inferred primarily from individual analyses of each group. Therefore, any differences should be interpreted with caution, as they may indicate emerging trends rather than definitive conclusions.

7.4 Considering the collective evidence for semantic contributions to verbal short-term memory

The set of studies comprising this thesis have demonstrated influences on semantic information of various forms in vSTM, supporting that the contribution of semantic knowledge is more significant than recognised following traditional accounts that have generally postulated that phonological features primarily drive vSTM (Baddeley, 1966, 1986; Baddeley & Hitch, 1974). Some of the key conclusions drawn from the current research, relevant to all participants and replicating previous findings, is that semantic knowledge supports the stability of the phonological trace (Chapter 5 and 6), the appropriate recall of item sequences (Chapters 3, 5, and 6), and even contributes to the recall of phonetically unfamiliar nonwords (Chapter 6). A cornerstone to these findings is the careful methodological designs employed. Notably, semantic manipulations have been applied while controlling for most phonological-lexical properties such as frequency and length, allowing the isolation and examination of semantic effects beyond the likely relationship between semantic strength and lexical availability due to frequency of occurrence.

While hallmark observations of specific reductions in phoneme migrations were not always observed, Patterson et al.'s (1994) semantic binding hypothesis offers a credible interpretation for the outcome of semantic manipulations across this PhD. Overall, semantic representations seem to strengthen the activation of words' phonemes, thereby increasing their recall accuracy and diminishing the chances of phoneme migrations, as observed in Chapters 5 and 6. Such conclusions support recent reconsiderations of the position of vSTM within the cognitive architecture. The traditional dichotomy between language processing and memory may not adequately represent their interrelationship. Instead, it seems more accurate to envision vSTM as an emergent property of language system activation, which is dynamically influenced by both phonological and semantic elements (Acheson & MacDonald, 2009b; MacDonald & Christiansen, 2002; Majerus, 2013; N. Martin & Saffran, 1997; R. C. Martin et al., 1999; Patterson et al., 1994; Schwering & MacDonald, 2020). It may not be merely about maintaining phonological forms in a modular buffer, but a complex interplay between different components of the language system.

However, it is also essential to acknowledge the likely contribution of strategic reconstruction to recall performance, as proposed by redintegration accounts (Hulme et al., 1991, 1997; Schweickert, 1993a). These argue that lexical and semantic knowledge impacts vSTM at the recall stage, helping to reconstruct the degraded phonological trace by selecting the correct lexical candidate. Based on this, a redintegration process may explain the correct recall of items of words in mixed lists without reducing phoneme-level errors, but is far less suited than the semantic binding hypothesis to explain the impact of semantic factors on nonword recall. This is because, according to redintegration accounts, while the phonological trace decays, there are no effects of lexicality and no intervention of long-term knowledge. This implies that the lexicality of one item in the list should not impact other neighbouring items in the list, which contradicts findings of Chapter 6. Thus, it could be that the impact of semantic binding and strategic reconstruction represent two complementary facets of lexical-semantic contributions to vSTM. One fortifies the phonological trace by binding it with lexical-semantic information, while the other assists in reconstructing the decaying trace using lexical-semantic knowledge.

To sum up, the impact of semantic representations on phoneme movements within vSTM underscores the multifaceted role of the language system in vSTM. It indicates that language processing and memory are not separate cognitive domains but are intertwined, with the semantic and phonological systems working together to optimise vSTM performance. Besides, it is important to consider how different types of semantic knowledge may affect vSTM, since distinct processes are underlying the effect of semantic relatedness, imageability, semantic coherence, and newly acquired semantic representations.

Do the different types of semantic information operate in the same way in verbal short-term memory?

In Chapters 2 and 3, I investigated the impact of recently acquired multimodal novel semantic knowledge, drawing together conceptual associations related to object form, function, and context on vSTM. This methodology was previously employed by Savill et al. (2017) to assess the individual contributions of phonological-lexical and semantic representations to vSTM. The design provided a means to ensure meticulous control over the number of semantic features associated with each phonological form. An effect of newly acquired semantic knowledge was found at the item level only, when the set of stimuli to be learnt was reduced. In the context of language learning and vSTM, the lack of a semantic effect at the phoneme level could be attributed to the nature of the associations between the nonwords and semantic information. In both studies, the nonwords were associated with either blurred images or images of unfamiliar objects coupled with written descriptions, but it is possible that these associations (whether fully-formed or partial), or memories for presentation of the words themselves, were primarily episodic in nature rather than establishing robust semantic representations and/or lexical-semantic associations. That is, when learning new phonological forms, especially nonwords, the focus may primarily be on the phonological and acoustic properties rather than their semantic meaning. The associations might have been more episodic, reflecting the specific context of the experimental task, rather than eliciting the establishment of long-term semantic representations. As a result, the potential influence of semantic knowledge on vSTM performance may have been constrained.

The semantic binding hypothesis (Patterson et al., 1994) framework implies that the phonemes of a word are anchored by the lexical-semantic knowledge that, over time, has tied to the sequence of phonemes within the word, thus emphasising the role of semantic information in strengthening the phonological trace. However, when learning novel phonological forms, especially nonwords, the focus might be predominantly on the phonological and acoustic aspects over their semantic significance. This might especially have proven to be the case in the absence of established long-term semantic representation to anchor lexical forms to, with novel associations that might not yet be ‘meaningful’. Due to the brief single session training paradigm, any association effects formed during these studies might have been shallow and primarily episodic, pertaining more to the specific context of the experimental task.

Episodic memory traces are characterised by their sensitivity to the encoding context and the specific details of an event (Tulving, 1993). In the studies described, the training tasks involved the presentation of nonwords and their visual/written pairings, which could create specific episodic memory traces for each association. Such episodic traces would have likely facilitated the retrieval of items during the vSTM recall tasks.

The possibility that words may have been retrieved via recent episodic memory instead of via established long-term lexical-semantic associations could explain the absence of an additional significant semantic effect at the phoneme-level of vSTM performance, since such representations would be fundamental for a semantic binding mechanism. It is important to note that episodic memory and semantic memory are interconnected, and information from one system can influence the other. However, in the specific context of the studies discussed, the focus on novel phonological forms and the nature of the associations might have led to a greater reliance on episodic memory traces, in place of fully established semantic representations.

Chapter 5 and 6, which dealt with support from real, meaningful words, investigated the effects of semantic relatedness, coherence, and imageability on vSTM. Semantic relatedness (Chapter 5, Experiment 2) and coherence (Chapter 6) both activate shared semantic nodes (Lambon Ralph et al., 2017), which could enhance inter-item recall in vSTM, while imageability predominantly influences individual words' internal structures by connecting them to a network of semantic features (Binder et al., 2009; Roxbury et al., 2014; Sabsevitz et al., 2005), potentially boosting their recall chances. Before delving deeper, it is worth noting that effects of semantic relatedness and coherence are relatively more pronounced than imageability. They will likely inherently benefit from redintegrative, strategic, or chunking processes: when words are semantically related or coherent, they tend to be grouped together in the memory, forming 'chunks' of information that can be more easily recalled. This chunking strategy enhances performance in vSTM tasks by reducing cognitive load and streamlining retrieval processes (Miller, 1956).

However, it is likely that these processes are not the sole factors at work. In the context of semantic relatedness, explored in Chapter 5, the enhancement of memory span for related items could be attributed to the formation of semantic networks, where semantically related items are interconnected. According to Kowialiewski et al., (2022), when an item is encoded into vSTM, the activation spreads through the network to related items, thereby strengthening the memory trace of not only the initial item but also the associated items. This increased activation would enhance retrieval processes, leading to improved vSTM performance for semantically related lists, as observed in this thesis. This implies that long-term linguistic knowledge may play a role from the encoding stage, opposing the redintegration-based models' assumption of intervention only when vSTM traces degrade (e.g., Schweickert, 1993).

The vSTM advantage for semantically coherent word lists (Chapter 6) is predicated on shared conceptual knowledge amongst words, giving them a common context that boosts recall. Semantic coherence may reinforce activation levels, paralleling semantic relatedness, and supports the integral role of semantic networks in vSTM (Dell et al., 1997; McClelland & Rumelhart, 1981). Semantic coherence demonstrated stabilisation of both words and nonwords in vSTM, enhancing recall accuracy by preventing phoneme separations and reducing migrations. This suggests the potential to provide cumulative semantic strengthening beyond the activation limits of single word imageability. Nonetheless, imageability appears to have a unique impact on vSTM (at least compared to the other semantic variables tested) as its influence correlates with phonological abilities.

Interestingly, in Chapter 5 (Experiment 1), the relationship between phonological skills (indexed by nonword recall performance) and semantic effects was only clearly observed under fast presentation conditions when imageability was manipulated. Such a relationship was only weakly evident when semantic relatedness was manipulated, further highlighting the unique contribution of imageability, or at least the intrinsic semantic values of individual words. Individuals with weaker nonword performance, indicating difficulties in engaging with novel phonological forms without the aid of lexical-semantic context, demonstrated a stronger imageability effect under challenging conditions. This further substantiates the primary systems hypothesis (Patterson & Lambon Ralph, 1999), as an increased presentation speed would exert more pressure on the phonological system, necessitating a heightened dependence on the semantic system. The semantic system, in this instance, might then be perceived as a critical support network that ensures the proper encoding, retention, and recall of phonological forms, even when under significant stress.

What might make imageability unique with respect to its sensitivity to phonological context? By definition, imageability captures a form of semantic richness that extends beyond simply the ability to generate a mental picture (Binder et al., 2009; Paivio, 1991;

Roxbury et al., 2014; Sabsevitz et al., 2005). The potential automaticity of this process may be tied to the way the word forms are intricately woven with their semantic representations. This could make these words more readily accessible, independent of explicit task strategies, and possibly linking them with other related measures not explicitly tested here, such as age of acquisition (AoA), number of features (NoF), and concreteness, which are typically all highly correlated with imageability. If we controlled for or manipulated these variables, we would probably have seen similar results. For instance, words with an earlier AoA or higher NoF could be more easily recalled, like high-imageability words. Imageability's utility may stem from its multidimensionality, encapsulating aspects of AoA, NoF, and concreteness, and providing a composite semantic representation. This could make high-imageability words resilient to phonological disruptions, aiding recall especially in those with phonological difficulties, like dyslexic individuals. The key insight here is not imageability itself but the overall semantic richness it signifies, potentially enhancing vSTM performance.

Chapter 5 (Experiment 1) yielded compelling evidence that high imageability words, those evoking vivid mental images or sensory experiences, outperform their low imageability counterparts in recall performance, regardless of presentation rate. This finding suggests that imageability's impact remains robust, even under rapid encoding conditions, thus diminishing the need for extended rehearsal or strategic elaboration. The lack of modulation in the imageability effect with increased presentation speed in our study challenges the conclusions of Campoy et al. (2015), who suggested that a slower pace enhances imageability. Our findings instead underscore the automaticity of imageability effects. Kowialiewski and Majerus's study (2018), on the other hand, noted the absence of the imageability effect in a running span task with unpredictable list length, regardless of the pace of presentation. However, the effect was observed under standard ISR conditions, albeit not tested at faster speeds. In such scenarios, the time available for recall, unlike in running span tasks, means residual semantic/visual activation could guide reconstruction and amplify imageability effects. However, our research offers strong evidence that the influence of imageability is independent of inter-item intervals and may arise under specific task requirements. The differential task demands could therefore contribute to varying outcomes, suggesting that the impact of imageability might be more closely tied to task-specific demands, such as serial order recall or continuous memoranda updates, than to the duration of the inter-item interval.

Overall, the differential relationships of imageability and semantic relatedness with nonword performance can be attributed to the distinct ways these semantic factors engage with and influence vSTM. Imageability provides an individual word-based semantic scaffold that is particularly beneficial for words when phonological processing is challenging. In contrast, semantic relatedness and coherence offer a broader contextual framework that benefits the entire list, regardless of the performance of individual items. This intra-item and inter-item differentiation reveals the special nature of imageability within the context of semantic influences on vSTM. Imageability represents a form of semantic knowledge that affects the internal structure of individual words, while semantic relatedness/coherence affects the relationships between words in a list.

7.5 Examining semantic compensation in dyslexia: Evidence and implications

Prior evidence indicates individuals with dyslexia may tap into their knowledge of word meanings, context, and language structure more extensively than their non-dyslexic counterparts to facilitate reading and offset challenges in decoding and word recognition (Betjemann & Keenan, 2008; Cavalli, Duncan, et al., 2017; Deacon et al., 2019; Hennessey et al., 2012; Klimovich-Gray et al., 2023; Nation & Snowling, 1998a, 2004; Nobre & Salles, 2016; Shaywitz et al., 2003; Stanovich, 1980b; van der Kleij et al., 2019; van Rijthoven et al., 2018; Vellutino et al., 2004b). This phenomenon is known as semantic compensation, which refers to the potential for individuals with reading difficulties such as dyslexia to use semantic information as a means to support or compensate for their phonological difficulties.

While the concept of semantic compensation is frequently acknowledged within dyslexia research, it is worth emphasising that this dialogue often neglects crucial perspectives offered by vSTM models and the primary systems hypothesis (Patterson & Lambon Ralph, 1999; Plaut et al., 1996). Verbal short-term memory models provide a detailed understanding of how semantic and phonological information is temporarily stored and manipulated during language processing, which can be incredibly valuable when investigating how individuals with dyslexia might compensate for their phonological difficulties. On the other hand, the primary systems hypothesis posits that the semantic and phonological systems are integral to a broad range of language activities, further emphasising the interplay between these two systems. By neglecting these frameworks, the exploration of semantic compensation in dyslexia might have been missing out on valuable insights and the chance to develop a more nuanced understanding of this phenomenon.

Additionally, it is important to note that the majority of research on semantic compensation has focused on children with dyslexia (Hennessey et al., 2012; Nation & Snowling, 1998b, 2004). This focus leaves a significant gap in our understanding of how these compensatory mechanisms may function and evolve as dyslexic individuals mature. Adults with dyslexia may have developed more sophisticated or varied strategies for leveraging semantic information to aid their reading and language processing, and these strategies might be substantially different from those employed by children (Cavalli, Duncan, et al., 2017; Deacon et al., 2019). Thus, a comprehensive understanding of semantic compensation in dyslexia necessitates the investigation of these mechanisms in adult populations as well (Klimovich-Gray et al., 2023; Nobre et al., 2016).

The research conducted in this thesis represents a significant stride towards bridging the existing knowledge gap, investigating potential lexical-semantic compensation in dyslexic adults within vSTM. Two possible levels of semantic compensation effects that might support vSTM were hypothesised. Firstly, the phonological difficulties associated with dyslexia could lead to relatively enhanced semantic effects compared to non-dyslexic adults, indicating an amplified sensitivity to, and perhaps reliance on, available lexical-semantic information. This would provide compelling evidence for the occurrence of semantic compensation. Alternatively, especially given that semantic effects are likely to be of modest magnitude over and above lexical knowledge (Jefferies, Frankish, & Lambon Ralph, 2006b), it was plausible that the effects of lexical-semantic variables would be comparable between the two groups. This could also index compensatory support, such that using available lexical-semantic knowledge helps to compensate for their phonological difficulties by lifting performance to a ‘normal’ level; above what might be expected based on phonological performance without it. That is, if the baseline performance for nonwords is lower in the dyslexic group but becomes comparable to non-dyslexic for words when lexical-semantic representations are available, it would suggest some lexical-semantic compensation.

The findings across the research comprising this thesis point to the second scenario: dyslexic individuals could maintain performance parity with non-dyslexics when presented with lexical-semantic content, whereas dyslexic participants tended to be poorer than non-dyslexic participants when this was not available (i.e., for nonword recall). We had expected adults with dyslexia to be facing relative phonological and vSTM challenges, which appeared to be borne out, and their vSTM performance was comparable with the provision of lexical-semantic representations.

Even though interactions between participant group and semantic effects were not significant across studies, there were suggestions of some potentially relevant differences between groups: the effect of imageability on phoneme migrations (Chapter 5) seemed to be more pronounced in the dyslexic group, and semantic coherence effects (Chapter 6) were found to be more substantial in the dyslexic group than in the non-dyslexic group for items recalled in the correct serial position. Such relatively stronger boosts may indicate – at least partially – some developed stronger weighting of (orientation to) lexical-semantic knowledge, presumably to compensate for their phonological difficulties. Even though the phonological system might be weakened in dyslexia, typical vSTM performance can still be achieved through the support of the lexical-semantic system. This is consistent with the primary systems hypothesis (Patterson & Lambon Ralph, 1999) and related interactive-activation models, as it seems to illustrate the interaction between primary linguistic systems. Additionally in sync with the PSH, the observed relationship between nonword recall and the effect of imageability in fast ISR suggests that these adaptive strategies may be more pronounced or visible in demanding or challenging contexts.

The extent to which semantic knowledge might assist vSTM beyond the influence of lexicality must be acknowledged. Throughout the studies conducted in this thesis, phonological-lexical effects were prominently and consistently demonstrated, whereas the impact of semantic variables was less pronounced. This perhaps is not surprising. The capacity of semantic assistance will likely have its limits, in that we would not expect its potential benefit to increase indefinitely. Essentially, the support available from semantic resources can only go so far, depending on the baseline for recall performance. Since the reach of this support is finite, this suggesting that even though semantic effects were not strongly evident behaviourally, they could still be at play. The numerical trends across different tasks hint that this may often be the case.

The tendency to observe no group interactions with the ISR manipulations prompt a contemplation of open science, and the challenge of publishing non-significant results or findings of no substantial difference. For instance, a study by Rasamimanana et al. (2020), which examined semantic compensation in word learning, found no discernible behavioural differences between adults with and without dyslexia. Yet, given the frequentist analyses employed by the authors, the inconclusive results did not permit any robust conclusions. This partly motivated the use of Bayesian analyses in this thesis, which can discern between a lack of evidence towards the alternative hypothesis and evidence in favour of the null hypothesis. It indicated that the lack of interaction was not due to a lack of power, but may simply not occur. Considering the primary systems hypothesis (Patterson & Lambon Ralph, 1999) and previous findings suggesting semantic compensation in reading (Hennessey et al., 2012; Nation & Snowling, 1998b; Vellutino et al., 2004b), the exploration of semantic compensation in vSTM in dyslexia appeared self-evident. Nevertheless, to my knowledge, there are no published studies undertaking such an investigation. It seems unlikely that this mechanism has never been researched before in vSTM tasks, and point towards the necessity to use more flexible and nuanced statistical tests, which can facilitate meaningful conclusions even in the face of null results.

Related to this, it is important to acknowledge that, while the intention of this PhD of extending study to dyslexic populations to examine whether the magnitude of lexical-semantic support in STM scales with phonological difficulty was premised on difficulties in dyslexia attributed to phonological processing and potential consequent semantic compensation effects, not all dyslexic individuals experience the same level of phonological difficulties (as shown by the overlap between dyslexic and non-dyslexic individuals at standardised phonological tasks such as the Spoonerisms task). Dyslexia is a complex and heterogeneous disorder (Wokuri et al., 2023), with variations in its manifestation and severity across individuals. The absence of strong evidence for semantic compensation in this work could be due to individual differences in cognitive profiles or strategies employed during vSTM tasks. In addition, the use of semantic information in dyslexia may vary across different stages of development. While research suggests that children with dyslexia may rely more heavily on semantic knowledge during reading tasks (e.g., Hennessey et al., 2012; van der Kleij et al., 2019), it is possible that this compensatory strategy diminishes or changes as individuals mature into adulthood. However, Cavalli et al. (2017) suggested that university students with dyslexia who were more proficient in utilising morphological knowledge as a compensatory strategy had developed enhanced reading skills, although the specific cause-and-effect relationship was not directly examined (see also Cavalli, Colé, et al., 2017). It therefore seems possible that high-achieving individuals with dyslexia use morphosemantic knowledge as a compensatory mechanism in reading, and possibly in vSTM contexts too.

Most importantly, perhaps, is the repeated observations across this programme of research that, despite (on average) relatively struggling with pure and standardised measures of phonological abilities (as expected based on the assumption of phonological weaknesses in dyslexia; Griffiths & Snowling, 2002; Hulme et al., 2005; Snowling, 2000; Swan & Goswami, 1997; Vellutino et al., 2004b), when our dyslexic adult participants were presented with meaningful material (carrying lexical-semantic information) such as words in ISR tasks, they no longer showed performance disadvantages compared to non-dyslexic participants. This echoes Wang et al.'s (2016) study, which reported no vSTM deficits for words in university students with a history of dyslexia when assessed using an ISR task, and underscores the potential of dyslexic individuals leveraging lexical-semantic knowledge to retain information in verbal short-term memory.

Since perceptual processing and the demands of repetition in vSTM does not require decoding (certainly has less decoding demand than reading) vSTM tasks ought to result in reduced need or contribution for lexical-semantic knowledge; thus, managing to observe such the pattern of lexical-semantic in vSTM may not be as pronounced as effects that might be seen in reading. According to a study conducted by Klimovich-Gray et al. (2023), increased top-down semantic processing in natural speech is linked to better reading in dyslexia. Reading, a context-rich activity with narrative elements and prediction cues, could potentially allow dyslexics to draw more on semantics to comprehend the gist (Nation & Snowling, 1998a). Dyslexic adults seem to navigate these tasks effectively by capitalising on semantic processing and leveraging contextual facilitation. Similarly, Nation and Snowling (1998) showed that children with dyslexia employ semantic context as a compensatory mechanism to mitigate the impact of their poor decoding skills when engaged in reading text. It is noteworthy that the semantic compensation in dyslexia is more apparent in tasks that require language comprehension. Dyslexic individuals may use their long-term knowledge, existing lexical representations, and prediction abilities to compensate for phonological deficits in natural speech and reading. They might also draw on broader contextual cues, which provide a richer semantic scaffold for comprehension. These compensatory strategies may be more pronounced in sentence-level comprehension tasks, providing richer context for semantic processing, than in immediate serial recall tasks.

Semantic compensation – or observable semantic compensation? - may thus depend on task demands. Certain tasks may require more phonologically based processing, making it challenging for dyslexic individuals to rely on semantic information. If the task primarily emphasises phonological processing and manipulation, individuals with dyslexia may struggle to compensate using semantic knowledge. Verbal short-term memory tasks typically involve the temporary storage and recall of verbal information over a short period. Tasks such as immediate serial recall, digit span, or word span often rely heavily on phonological processing and maintenance of accurate serial order. In these tasks, the sequential and phonological demands may overshadow the potential benefits of semantic compensation. Dyslexic individuals may struggle to rely solely on semantic knowledge when the primary focus is on accurate phonological representation and recall.

In conclusion, dyslexic individuals seem to make use of lexical-semantic information around, and to potentially offset, their phonological difficulties in vSTM. This aligns with the primary systems view, which posits that the semantic and phonological systems interact to support a wide array of language activities. The extent of semantic support, however, appears to have limitations. Although semantic effects were evident in this thesis, they were not as robust as phonological-lexical effects. This suggests that semantic support may only be able to assist to a certain extent, dependent on the baseline of recall performance. Nevertheless, this support is still valuable, indicating that individuals with dyslexia might employ compensatory strategies that utilise lexical-semantic knowledge to bolster vSTM performance.

Moreover, semantic compensation might be contingent on task demands, the severity of phonological difficulties, and possibly the individual's stage of development. It is also important to consider that attentional difficulties and comorbid conditions common in dyslexia might impact this mechanism. The key question that remains is how prevalent and effective semantic compensation is amongst adults with dyslexia. This query is of great interest given that most of the existing research in this area has focused on children, and until this thesis, semantic compensation within the context of vSTM had not been thoroughly explored in adults. More research is needed to fully understand the mechanisms and limitations of this compensatory process, yet this thesis offers a significant step forward in understanding the potential role of semantic compensation in dyslexia within vSTM tasks.

7.6 Integrating neurobiological perspectives: Linking dyslexia, verbal short-term memory, and lexical-semantic effects

The pattern of results in this thesis aligns well with our current understanding of the neurobiological underpinnings of both vSTM and dyslexia. When we consider these findings in conjunction with Majerus's (2019) vSTM model and available neuroimaging research in dyslexia (e.g., Richlan et al., 2009), relevant links begin to emerge.

Poorer nonword capacity in dyslexic individuals observed in this thesis can be associated with underactivation of brain regions involved in phonological processing and reading, such as the left inferior frontal gyrus, which is involved in phonological and articulatory processing, the posterior superior temporal gyrus, involved in phoneme processing and auditory-motor integration (see regions depicted in red in **Figure 7.1 Panel B**, Démonet et al., 2004; Richlan, 2012, 2020), and, in particular, the left parietal regions including supramarginal gyrus, which is a hallmark of hypoactivation in dyslexia (Hoeft et al., 2007; Paulesu et al., 2001; Shaywitz et al., 1998). These regions have similarly been associated with phonological processing in vSTM (depicted in red in

Figure 7.1, **Panel A**, Majerus, 2013, 2019; Savill et al., 2015). These regions' roles in vSTM become particularly salient when processing nonword material. Thus, the underactivation observed in dyslexia in these regions could explain the difficulties that individuals with dyslexia experience in vSTM tasks, particularly those involving the short-term maintenance of phonological and serial order information.

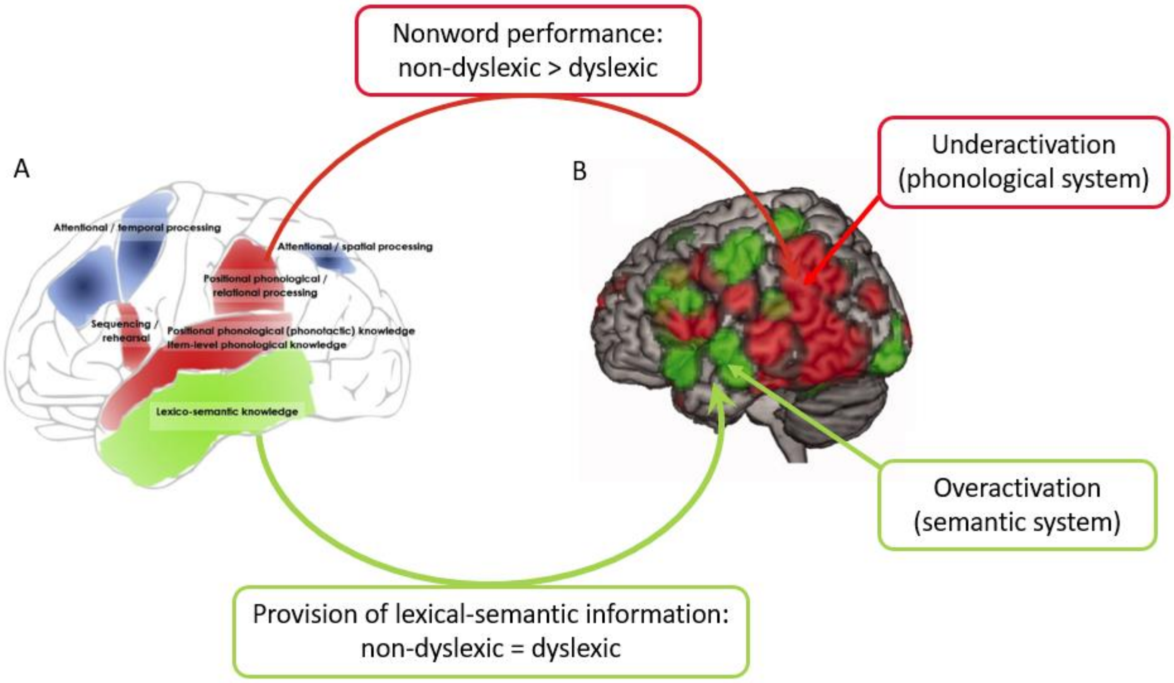

Figure 7.1. *Linking Majerus's (2019) verbal short-term memory model, verbal short-term memory performance for nonwords and words that benefit from lexical-semantic representations in the dyslexic versus the non-dyslexic group, and the pattern of under- and overactivations in the dyslexic brain in reading, as per Richlan et al. (2009).*
Panel A: *Majerus's (2019, p. 128) model where regions in the middle and inferior temporal gyri (depicted in green) are associated with lexico-semantic knowledge. Regions in the superior temporal gyri (depicted in red) are related to sublexical phonological knowledge about phonemes and their transition probabilities. The supramarginal gyrus is involved in the coding of list-level serial order information. This region can also support the temporary representation of item information.* ***Panel B:*** *Underactivations (depicted in red) and overactivations (depicted in green) in the reading systems of the dyslexic brain according to Richlan et al.'s (2009) meta-analysis of neuroimaging studies.*

However, when lexical-semantic information is provided, performance levels between dyslexic and non-dyslexic individuals tend to equalise. This might be attributable to the recruitment of hyperactivated areas in dyslexic individuals (illustrated in green in **Figure 7.1**, Pugh et al., 2000), such as the anterior temporal lobe—known for its role in semantic processing (Lambon Ralph et al., 2017; Patterson et al., 2007). In these contexts, it can be hypothesised that dyslexic individuals use their semantic system to a greater extent than their non-dyslexic counterparts, helping to bridge the performance gap in vSTM tasks. The necessity for this compensatory strategy might arise from the underactivation of areas responsible for phonological processing, resulting in difficulties during nonword recall tasks.

The observations of general similar effects of lexical-semantic properties between our participants across this programme of research may then make sense in light of Majerus's (2019) model with respect to its neurobiological distinctions in STM function: While the retention of item information, related to ventral language regions, heavily relies on lexical-semantic knowledge, order information primarily depends on phonological representations with minimal involvement of lexical-semantic knowledge, with order ascribed to superior parietal regions (for a review see Majerus, 2019). It has been suggested that the deficit in vSTM in dyslexia predominantly affects the processing of serial order (for a review see Majerus & Cowan, 2016). Thus, a possibility could be that because dyslexic participants have difficulties with order, and because order information may not be impacted by lexical-semantic factors, dyslexic participants would not be able to access this type of information to compensate their deficits. Nevertheless, certain studies have documented the impact of semantic knowledge on order retention, implying an interaction between serial order and linguistic knowledge in vSTM (Acheson, MacDonald, et al., 2011; Kowialiewski, Gorin, et al., 2021; Kowialiewski, Lemaire, et al., 2021; Poirier et al., 2015). These findings suggest that semantic variables may have the potential to enhance the vSTM performance of individuals with dyslexia.

Yet, it is crucial to approach these explanations with caution. Although neuroimaging evidence provides interesting correlations, it does not adequately establish causality or highlight the exact cognitive mechanisms behind these activation patterns. Further research using neuroimaging techniques to investigate lexical-semantic compensation in dyslexia, by comparing neural activity in dyslexic and non-dyslexic individuals during vSTM tasks with varying phonological and semantic demands, could provide clarity here. This approach would help uncover the nature of semantic compensation strategies and their neurobiological underpinnings.

7.7 Limitations and directions for future research

While limitations of the studies conducted as part of this thesis have been reported in individual discussions, it is essential to emphasise key points which will lead to suggestions for future research, before reaching the final conclusions. To effectively present these points, the following list of limitations and suggestions has been structured as numbered entries:

1. Regarding studies that involved a learning component (Chapters 2, 3, and 4), the potential lack of establishment of semantic representations in long-term memory (see Davis & Gaskell, 2009) was evoked multiple times, and even though no effect of overnight consolidation was found in Savill et al. (2017), future research should examine semantic effects at different time points (e.g., immediately after training, one day after training, and one week after training). Considering evidence showing that a period of consolidation promotes the integration of newly leant words in the mental lexicon and the establishment of their semantic representations (Clay et al., 2007; Davis & Gaskell, 2009; Hawkins, 2015; Tamminen & Gaskell, 2013), this could allow for stronger and meaningful effects of semantic knowledge to emerge in vSTM.
2. Another limitation within the learning studies conducted in this thesis was the reliance on the visual presentation of written data. This method, which included written image descriptions in Chapters 2 and 3, as well as written English words paired with auditory nonwords in Chapter 3, could have influenced the learning process for participants with dyslexia. Importantly, this potential effect did not result in observable group differences between dyslexic and non-dyslexic participants in learning accuracy, which could have complicated subsequent group comparisons during ISR tasks. Instead, this is likely to have affected participants' response times during the semantic tasks (Chapters 2 and 3), given the slower, more effortful reading typically exhibited by individuals with dyslexia (Pennington et al., 1990; Snowling et al., 2000). The existing body of research on multimedia learning presents diverse findings concerning the usage of oral or written information in

conjunction with images for learning (see Ginns, 2005; Mayer & Fiorella, 2014). Schweppe and Rummer (2016) proposed that while oral presentation aids short-term learning, written presentation facilitates long-term information retention. Consequently, to enhance the learning of new phonological forms, it might be advantageous to incorporate both written and oral presentations.

3. An additional limitation specific to Chapters 2 and 3 arises from the difficulty in distinguishing the association effect on learning. Specifically, the differences in learning outcomes could be attributable to the association effect, namely differences in the difficulty of acquisition between Familiar (FAM) and Semantic (SEM) items, versus the effects of LTM. The challenge is considerable as any differences may reflect the quality of the learnt phonological form. This was something the inclusion of an EEG component was intended to shed light on, by providing an implicit measure of the acquisition of phonological forms. However, this complexity remains, and future research should aim to design methodologies that can more effectively tease apart these components and their influence on learning outcomes.
4. Further considerations emerge when examining the EEG component of Chapter 2, particularly concerning the design of the task. This study specifically examined the precision of newly formed phonological representations by utilising the MMN, an electrophysiological indicator of auditory discrimination. Yet, the study design was somewhat constrained, as it tested the acquisition of only one set of nonwords. This constraint emerged due to the nature of EEG data collection, which requires numerous trials to attain robust and reliable data. Thus, the inclusion of multiple sets of nonwords for testing would have greatly increased the length of the experiment, potentially leading to issues such as participant fatigue. Nevertheless, this focus on a single set of nonwords might have affected the breadth of insights derived from the study, limiting our understanding of how these processes might vary across different types of nonwords or under different learning conditions. Regrettably, the unforeseen constraints

imposed by the COVID-19 pandemic precluded the possibility of conducting further EEG studies within the timeline of this PhD.

Further follow-up studies using neuroimaging technologies such as EEG and fMRI or MEG could enhance our understanding of the thesis results, particularly in two key areas:

Firstly, to distinguish between redintegration and language-based perspectives of vSTM, it would be beneficial to use EEG to examine Event-Related Potentials (ERPs) at various stages of immediate recall, including encoding, maintenance, and recall. This approach could illuminate whether an encoding advantage exists for semantic lists, a finding that would lend support to language-based theories. Additional experiments introducing a dual task during encoding or retrieval could further challenge this distinction, potentially revealing how different cognitive loads might influence these processes. Furthermore, the mixed list methodology, as employed in this thesis, seems to provide valuable insights in differentiating between redintegration and language-based accounts of vSTM. Therefore, applying this methodology with other semantic variables such as semantic relatedness, imageability, and nonwords associated with meaning could uncover further nuances in these theoretical perspectives.

Secondly, using neuroimaging techniques in vSTM tasks with dyslexic participants might help elucidate the neural underpinnings of their memory processes. Rasamimanana et al. (2020) observed in their study, within a learning context, that dyslexic individuals appeared to recruit their frontal resources more heavily in comparison to non-dyslexic counterparts. This over-reliance on frontal regions could be indicative of alternative neural strategies or adaptive mechanisms. Translating this observation to vSTM tasks, these techniques could determine whether similar frontal recruitment occurs when dyslexic individuals are presented with words that possess varying degrees of semantic richness. Alternatively, given the functional dissociations that have been observed in support of different types of linguistic materials (Majerus, 2019; Savill, Cornelissen, Pahor, et al., 2019; Verhaegen et al., 2013), neuroimaging techniques might reveal relative differences in activation that relate to lexical-semantic processing that might not be observable behaviourally. If such patterns were observed, they could provide further evidence for the adaptive neural strategies dyslexic individuals employ and might offer clues about how semantic information is processed during short-term recall tasks.

5. As alluded to earlier, adults with dyslexia in this thesis demonstrated a wide range of phonological skills. The research could have benefited from more precisely defined groups based on these phonological abilities. Future investigations could strategically recruit dyslexic participants based on their phonological skill metrics. An open question to explore is whether dyslexic participants with *more* limited phonological skills would rely on semantic knowledge to a greater extent than those with stronger phonological abilities. Accordingly, it would be worthwhile to categorise the dyslexic group into subsets with higher and lower phonological scores to scrutinise their use of semantic knowledge in vSTM. This could lend additional support to the primary systems account, as we would anticipate individuals with dyslexia exhibiting weaker phonological skills to depend more on semantic information compared to those with better phonological scores. A further research direction would be to examine this phenomenon in dyslexic children who might rely more heavily on semantic support due to their still-developing abilities, as compared to well-compensated adults. An alternative approach would be to incorporate an articulatory suppression component into the ISR task to further strain the phonological system. Moreover, in light of the potential difficulties with order in vSTM in dyslexia, the use of alternate tests such as running span procedures or tests that downplay the need for retaining order information could offer additional insights into semantic compensation and vSTM difficulties in dyslexia. Lastly, while this thesis did not delve into the role of attention, future research could incorporate this element to examine its potential influence on dyslexic individuals' vSTM performance and their use of semantic knowledge.

7.8 Conclusions

The results of the studies conducted in this thesis support the idea that long-term linguistic knowledge, particularly phonological-lexical representations, but also semantic knowledge, contributes significantly to vSTM performance, and does so fairly robustly across variation in phonological skill. The findings align with contemporary theories, especially language-based models, and primary systems hypothesis, that highlight the relevance of interplay between phonological and semantic systems in vSTM. Merging these theories would involve acknowledging that the use of semantic information to support phonological processes, as posited by the SBH, is a specific instance of the more general principle proposed by the PSH - the semantic and phonological systems are primary systems that interact dynamically in a range of language tasks. This unified theory would provide a comprehensive understanding of the role of semantic and phonological processes in language and memory, encompassing both the detailed mechanisms involved in short-term memory tasks (as per the SBH) and the broader role of these systems in language processing (as per the PSH). The influence of semantic information, specifically imageability, semantic relatedness, and semantic coherence on vSTM, is evident across the different chapters. These findings affirm the importance of both semantic and phonological processes in memory encoding and retrieval.

Imageability, an intrinsic item-level lexical-semantic property distinct from contextual variables like semantic relatedness, coherence, and newly acquired semantic representations, seems to have a particularly useful role in vSTM in dyslexic individuals, influencing the ordering process. Imageable words could provide vivid mental anchors, potentially bolstering vSTM by providing a robust sensory cue. Their semantic depth and richness might not be present in the other types of semantic variables tested (Barsalou, 1999; Binder et al., 2005), and could provide a richer context for stabilising phonological structures in dyslexic adults. While semantic relatedness or coherence provide contextual connections, they might lack the direct, intrinsic visual/sensory association and/or strength of LTM activation that imageable words inherently possess. Similarly, newly acquired semantic representations, though valuable, might not be as deeply rooted or immediately accessible as the representations associated with high-imageability words.

Nevertheless, given that tasks like immediate serial recall prioritise phonological processing, and potential verbal short-term memory capacity is naturally constrained, the advantages of semantic variables might be relatively limited. In contrast, in activities that offer contextual and syntactic cues, like reading and natural speech comprehension, the influence of semantic representations may be more pronounced.

Overall, the body of work outlined here points towards a dynamic relationship between semantic and phonological processes in dyslexic adults, particularly within the context of vSTM. The primary systems view posits that individuals with dyslexia make use of semantic information to help offset their phonological difficulties, a phenomenon referred to as semantic compensation. However, while the presence of this strategy has been observed, its effectiveness and the extent to which it can improve vSTM performance appear to be limited. The impact of semantic knowledge seems to be secondary to lexical effects, implying that it may offer only partial compensation. Despite these complexities, the research suggests that individuals with dyslexia are able to employ their lexical-semantic knowledge to maintain normal vSTM performance.

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Appendices

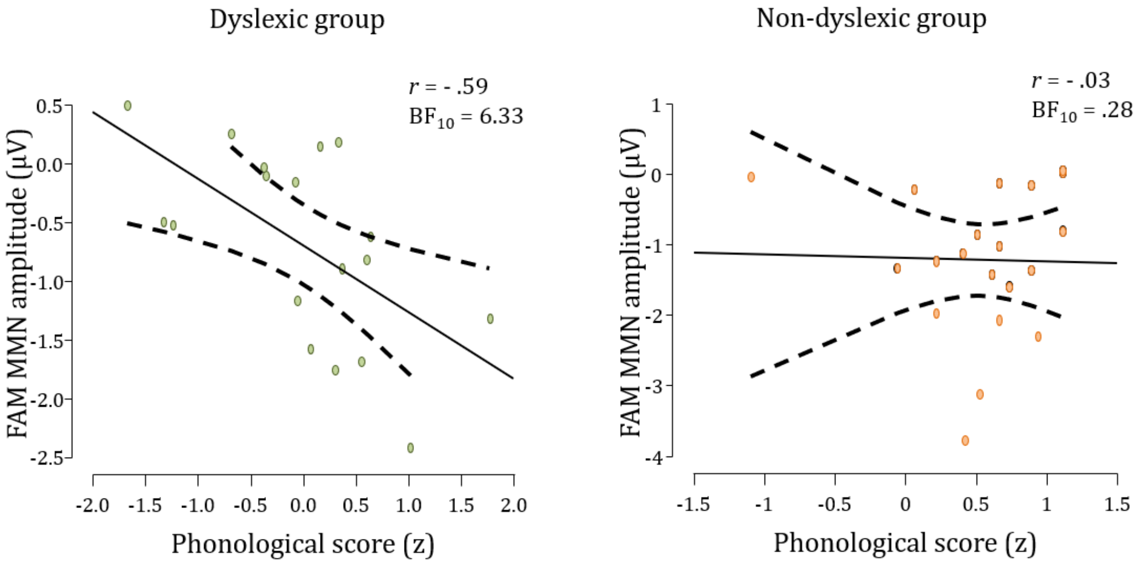
Appendix A

Nonword stimuli used in Chapter 2

badgick
barhooch
beeforn
bibe
bipe
bivvoal
boag
boap
boop
chaisoop
chappoize
cheeryab
chettoip
chowsoof
doachem
doathoik
doffout
duttarb
fedoosh
fickearce
flupe
foidesh
gairnoil
goap
gorpash
gudgearl
helloach
howyeg
hoyroat
jackairve
joohairn
joyzairb
kairbung
keersharp
kide
kipe
kodgine
koinash
kurrit
larthaze
leeroig
leerwize
loachouse
maihart
meewale
mepposh
moiwyne
mowwode
naimowd
nissowl
nookorth
peerzodge
pite
plabe
porp
pozzark
puzzoge
raveeg
reerbeep
rullitch
sairkeesh
seeg
seegark
sheeb
sherd
shevvipe
shoomice
shorneed
shyob
smode
snabe
soab
sormife
sube
thairgiss
thighweern
thoshort
throag
thuddorg
toovouge
toyim
vaitag
vuchozz
wairzorp
weeb
werb
whygooth
wohig
wybing
yaipyche
yarfive
yark
yart
yowmoof
zooshang
zowdeff

Appendix B

Additional analysis of the relationship between raw FAM MMN amplitude and phonological score in Chapter 2



***Appendix B**. Relationship between the phonologically familiar FAM deviant nonword MMN amplitude and phonological score. The dotted blue line depicts 95% confidence intervals.*

Appendix C

Nonword stimuli used in Chapters 3 and 4

pozzark
gudgearl
chappoize
doachem
thairgiss
fedoosh
nissowl
yaipyche
yark
chezz
voff
woog
meewale
gorpash
yoohairn
fickearce
zooshang
rullitch
howyeg
beeforn
yart
shodge
zeech
foib
vaitag
kurrit
leerwize
nookorth
mepposh
gairnoil
shevvipe
barhooch
soff
kide
jerze
detch

Appendix D

Immediate serial recall stimuli used in Chapter 5

***Table D1**. Stimuli used in the slow immediate serial recall task in Experiment 1.*

High-imageability words			Low-imageability words			Nonwords		
badge	gown	porch	bash	haul	ping	barme	knang	yoll
bait	gum	purse	beg	heave	pith	bearm	kov	yorch
barge	harp	rag	bog	horde	poise	bedge	kowce	
beak	hawk	ram	bosh	hove	pose	berm	lape	
beard	hearse	rash	botch	hub	pun	bish	larse	
beige	hedge	rib	budge	huff	rage	boaj	leng	
bib	herb	rice	cause	hurt	raid	carge	lerce	
booth	hike	roach	chard	hush	rate	chan	loat	
bun	hive	robe	chock	hype	retch	chate	molk	
cane	hog	rug	con	jig	rough	chegue	morth	
carp	hoop	shack	cud	jot	rout	chezz	narg	
cart	hose	shave	curse	jowl	sake	coaf	noik	
chef	hut	shawl	darn	keel	shale	cudge	nough	
chess	jog	shin	daze	kin	sham	darg	nutch	
chick	keg	soap	deaf	knack	shame	darp	paich	
chime	kite	sock	dearth	lack	sheen	dearl	pite	
chive	knob	sword	deed	lag	shock	dease	pooce	
choke	lace	teen	deuce	lame	siege	dooch	porg	
cob	lark	thong	din	lash	sieve	dorch	porve	
comb	latch	thorn	dirge	lass	sin	dozz	rawl	
cork	leash	thug	dole	lathe	soul	farze	rorm	
couch	ledge	tile	don	lease	surge	fim	ruv	
cough	leech	toad	doom	loom	thud	foise	san	
cuff	lice	tomb	dose	loss	toil	fowk	shadge	
curb	lip	tooth	doubt	louse	ton	futch	shang	
curl	loaf	tub	fad	lug	tone	gan	sheck	
dice	lodge	veil	fake	lurch	verb	gaut	shill	
dime	marsh	vine	farce	mead	verge	gerse	shorge	
dove	mauve	wart	fib	merge	vice	ghouk	sieth	
fang	maze	web	force	mirth	vogue	gife	soff	
fern	mice	wedge	forge	mode	wail	ging	sorl	
fig	mole	weed	foul	mooch	ward	goaj	sotch	
fork	moose	weep	fuss	muck	warp	harge	souge	
fowl	mop	wick	gab	mull	wharf	heef	tathe	
fudge	morgue	womb	gain	nag	whiff	heeZ	thacque	
gauze	moss	worm	gale	niche	wit	jerth	thuff	
geese	mutt	wreath	gall	nil	worth	jomb	thume	
germ	niece	yacht	gape	nip	wrath	jorve	vose	
ghoul	noose	yarn	garb	node	yap	jowd	wace	
gin	palm	yawn	gauche	nought	yen	kaish	wharve	

gnat	peach	yolk	guise	pace	yule	keech	widge
gnome	peg	zip	hack	pang	zeal	keem	wom
goat	pooch		harm	perk		keerg	woog
gong	poop		hate	phase		keng	wreague

Table D2. *Additional stimuli used in the fast immediate serial recall task in Experiment 1.*

High-imageability words			Low-imageability words			Nonwords		
bake	hen	whale	ban	hoard	whom	bem	hozz	lang
bark	hood	wheat	bane	hoot	wise	boage	jarve	lazz
bead	hoof	whip	beck	jag	wren	boove	jass	loace
buck	jug	wig	bout	jot	yearn	borge	jeem	loog
bug	lane	wipe	cam	mood	zing	borm	jile	lorf
bum	lawn		cease	myth		bowk	jom	marth
cage	leach		chap	nab		cheeg	keece	merk
cape	lick		cope	norm		chizz	keek	neff
cheek	limb		curd	noun		choan	keirce	nem
chin	lung		dab	null		chout	kiern	nong
coin	mace		dale	numb		daich	kish	norg
cone	mat		dame	pep		dal	korch	nuck
cop	mime		dell	pip		dav	korg	paig
cord	mob		dud	posh		deez	korge	parz
corn	moth		dull	rile		derch	shung	pooge
cot	mug		dumb	rude		doig	sonn	potch
cub	nail		fame	sane		dorce	sooch	pung
dart	nude		fate	seep		fersh	sorth	rame
dirt	nut		gob	shoal		fet	thaff	rard
ditch	pearl		gull	sill		fitch	thame	reng
dock	pill		gush	tame		foach	thut	ruve
doll	pine		harsh	theme		foap	tude	sarl
dorm	pouch		heath	toot		gace	viss	seef
fawn	pup		heed	tot		garge	werg	sezh
fin	rack		hid	vague		gart	woam	shike
foam	rake		loose	void		gath	woim	shorp
fog	rum		lurk	warn		gerk	worge	shudge
fuzz	surf		lush	wean		gowf	woss	shull
gem	thief		mart	wham		hage	korve	yarl
heel	thumb		mock	whim		hiff	kotch	yeege

Table D3. *Stimuli used in the slow ISR task in experiment 2.*

Semantically related triplets								
day	month	year	east	north	south	group	crowd	team
red	pink	green	long	tall	length	tree	branch	oak
hand	foot	arm	sin	bad	wrong	lip	mouth	tongue
love	hate	joy	gold	bronze	lead	crime	jail	law
glass	jar	cup	limp	cane	walk	knife	stab	blade
rain	cloud	storm	bus	car	truck	pearl	jewel	gem
talk	speak	chat	bed	sheets	sleep	mime	clown	act
milk	cow	farm	brick	stone	wall	mock	jeer	tease
rope	knot	string	phrase	word	book	breeze	air	gust
lake	swim	pond	few	scant	rare	war	fight	beat
pants	jeans	shorts	nail	screw	tool	clean	bath	soap
lung	heart	brain	gin	beer	rum	key	chain	door
nerd	geek	smart	thin	lean	small	clay	pot	mud
zen	peace	calm	fly	bug	wings	test	quiz	pass
snow	cold	ice	jot	pen	note	blind	sight	dark
wick	burn	lamp	sex	hot	lust	teen	age	kid
chew	spit	bite	dupe	cheat	trick	cook	chef	bake
ghoul	dead	spook	mote	dust	speck	fame	star	rich
grim	death	bleak	herb	sage	dill	haze	mist	smoke
chic	hip	cool	scum	crud	dirt	maze	lost	hedge
game	toy	fun	hug	kiss	care	grow	raise	thrive
grief	loss	cry	vent	duct	pipe	tray	dish	lunch
chaste	pure	white	fast	run	speed	sport	ball	gym
worn	used	old	soil	earth	brown	yell	cheer	loud
cut	chop	snip	sick	flu	ill	oat	grain	wheat
wax	hive	bee	queen	throne	reign	opt	choose	pick
rib	chest	meat	boil	steam	heat	path	through	way
shape	square	form	dare	risk	brave	sky	blue	moon
frog	toad	leap	hair	brush	wig	wheel	spin	round
eye	lash	brow	loom	cloth	thread	bin	trash	waste
tint	hue	dye	monk	nun	priest	prey	kill	hunt
nest	straw	twig	oath	swear	court	sea	fish	boat
pack	trip	bag	peak	climb	hill	swine	pig	boar
school	class	teach	poll	vote	ask	wool	coat	yarn
rack	shelf	stack	rash	skin	itch	help	give	need
rook	crow	black	scar	burn	mark	crust	hard	edge
shed	barn	wood	tack	pin	board	balm	soothe	cream
veer	turn	drive	song	tune	voice	fare	price	cost
weld	join	spark	void	hole	blank	jazz	blues	soul
nerve	spine	cell	stage	show	play	meth	drug	high
stamp	mail	post	gun	shoot	bang	wound	hurt	blood
bill	pay	charge	shrimp	prawn	krill	win	prize	gain
ram	sheep	goat	clench	squeeze	fist	mind	thought	head
pale	wan	light	rude	mean	cruel	dog	bark	pet

gas	fuel	oil	guess	think	try	split	break	half

__Table D4__. Additional stimuli used in the fast ISR task in experiment 2.

Semantically related triplets					
tint	hue	dye	grow	raise	thrive
nest	straw	twig	tray	dish	lunch
pack	trip	bag	sport	ball	gym
school	class	teach	yell	cheer	loud
rack	shelf	stack	oat	grain	wheat
rook	crow	black	opt	choose	pick
shed	barn	wood	path	through	way
veer	turn	drive	sky	blue	moon
weld	join	spark	wheel	spin	round
nerve	spine	cell	bin	trash	waste
stamp	mail	post	wound	hurt	blood
bill	pay	charge	win	prize	gain
ram	sheep	goat	mind	thought	head
pale	wan	light	dog	bark	pet
gas	fuel	oil	split	break	half
monk	nun	priest	void	hole	blank
oath	swear	court	stage	show	play
peak	climb	hill	gun	shoot	bang
poll	vote	ask	shrimp	prawn	krill
rash	skin	itch	clench	squeeze	fist
scar	burn	mark	rude	mean	cruel
tack	pin	board	guess	think	try
song	tune	voice			

Appendix E

Additional analysis of recall accuracy based on list length in Chapter 5, Experiment 2

Due to the considerable differences in the lengths of the lists in Experiment 2, an additional analysis was conducted to evaluate the effectiveness of semantic relatedness on CAP recall based on list length.

As can be seen on **Figure E**, it appears that recall performance decreases as list length increases (main effect of list length: $BF_{10} = 6.02*10^{60}$) which is expected: longer lists are typically harder to remember. Performance is also generally better in the related condition than in the unrelated condition ($BF_{10} = 4.16*10^{25}$). A weak effect of presentation rate was found, with better performance observed in slow rate condition ($BF_{10} = 2.45$). There was no main effect of group ($BF_{10} = 0.84$).

The impact of presentation rate seemed to be more prominent for longer lists (presentation rate by list length interaction: $BF_{incl} = 402598$). For example, the performance drop from a slow to a fast rate seems larger for a list of 12 items (39.3% to 36.8% for related and 28.1% to 27.2% for unrelated) than for a list of 6 items (86% to 79.3% for related and 69.7% to 65.7% for unrelated).

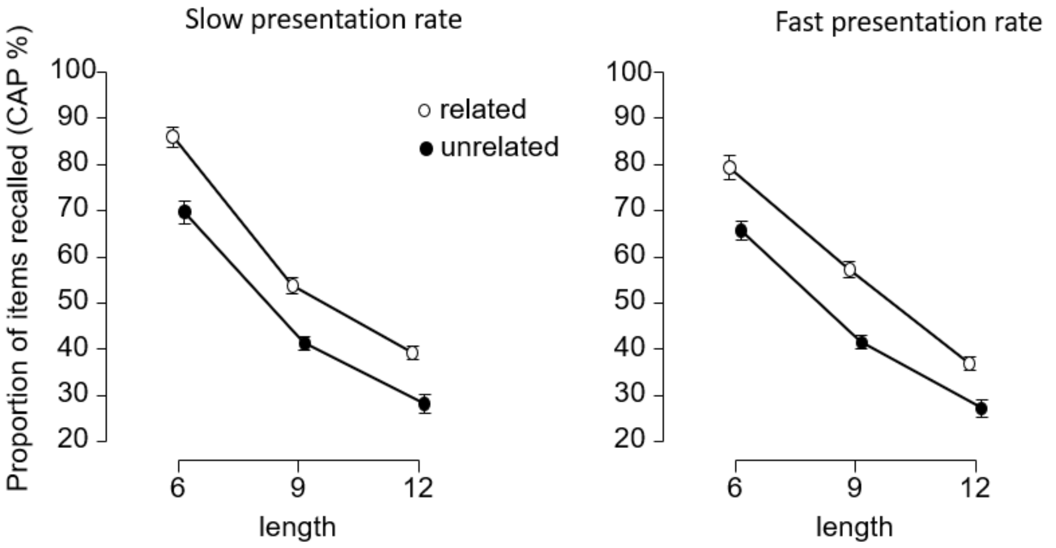


Figure E. *Proportion of items recalled in the correct position according to list length in the slow and fast presentation rate ISR tasks.*

Both dyslexic and non-dyslexic participants recall items from related lists better than from unrelated lists, regardless of list length. However, the advantage of relatedness seems to diminish as list length increases (list length by list condition interaction: BF_{incl} =3244.21). The decline in recall performance with increasing list length is more pronounced in the related condition than in the unrelated condition for both groups.

While the related condition generally leads to better recall performance at both slow and fast rates, the advantage of relatedness seems to diminish at a faster rate (condition by presentation rate interaction: BF_{incl} = 8.36).

Finally, the list length by list condition by rate interaction (BF_{incl} = 53.32) indicates that the relationship between list length and recall performance might be different depending on both the list condition (related vs unrelated) and the rate (slow vs fast). For the related condition, there is a decline in recall performance as the list length increases from 6 to 12 items. This decline is larger when presented at a slow rate (from 86% to 39%) compared to a fast rate (from 79.3% to 36.8%). This implies that even though related items usually enhance recall performance, this advantage diminishes somewhat when the list gets longer, particularly at a slower rate of presentation. On the other hand, for the unrelated condition, there is also a decline in performance as the list length increases, but the difference is slightly larger when presented at a fast rate (from 65.7% to 27.2%) compared to a slow rate (from 69.7% to 28.1%). This suggests that for unrelated items, the impact of increasing list length on recall performance might be slightly greater when the rate of presentation is faster. This complex interaction suggests that the speed of presentation and whether the items are related or not can differentially influence how list length affects recall performance.

Appendix F

Immediate serial recall stimuli used in Chapter 6

***Table F1.** Lists of semantically coherent words mixed with nonwords used in the ISR task.*

Semantically coherent lists mixed with nonwords					
chop	sutt	hedge	shears	thike	lin
storm	dod	waves	ship	lunk	raff
bral	sung	choir	loke	voice	tid
pyaze	nair	join	church	frooth	god
bold	stunt	frem	leap	jat	mon
sit	roose	lawn	nug	fide	breeze
heek	shul	prize	danned	worth	lots
drove	kimp	farze	pul	jaunt	south
boin	chide	koze	dirt	fleek	rug
hound	dorf	leash	fet	chay	park
tay	cook	mobe	nudd	grill	cheese
sUd	trail	wike	het	pitch	camp
teen	quorl	shop	glack	dress	mim
thief	blim	paith	dard	mug	ran
guv	club	dring	ball	swide	shot
cop	serl	deerf	thug	van	hess
loon	stalked	prarge	girl	yeng	chuss
shreed	kizz	wasp	stung	heerk	leg
shung	mix	tape	sairve	lonned	youth
wope	throb	head	sleen	beers	dack
late	tuss	bime	cab	work	ving
plays	droob	heart	soul	fyun	tav
berve	nest	trees	saff	chick	hade
chill	wet	ryook	kay	sneeze	han
besh	chose	rass	wine	steak	dom
gissed	band	wog	live	ferch	stage

***Table F2**. Lists of random words mixed with nonwords used in the ISR task*

Random lists mixed with nonwords					
sork	motch	card	jump	preet	face
preach	bar	shog	serk	wem	laid
peege	fit	shell	blorm	grave	nazz
laugh	thorge	tap	meck	seed	vabe
vest	deers	wanned	sish	buck	chong
hoce	thol	land	warm	chike	group
chuv	wheel	glome	sUg	herb	rat
cap	hive	lun	sink	zob	darch

norb
fun
forze
kind
woff
lipe
heece
wince
beat
stroke
mask
class
home
stoop
frint
nost
vosh
grooz
klim
tooth
glass
yoll
louse
chic
roize
taith
mip
kwIg
jug
weff
grop
kend
duck
poke
tark
chimp
race
yal
daid
barge
saig
gun
joint
pop
flag
nump
vont
gim
mesh
hile
narp
rorl
cream
mode
fedge
nost
heen
foot
cramp
swerd
bob
sul
coin
mess
keeve
road
bav
phrase
lend
hoop
choose
thet
put
week
swamp
sone
hoozh
bill
tedge
beef
trook
lord
hill
bipe
terge
pot
vake
verse
zay
waish
soap
mish
short
truzz
ten
noach
mark
hode
chell
jeef
foom
pat
cloud
merv
jazz
goized
lost
knife

Appendix G

Example ISR coding in Chapter 6

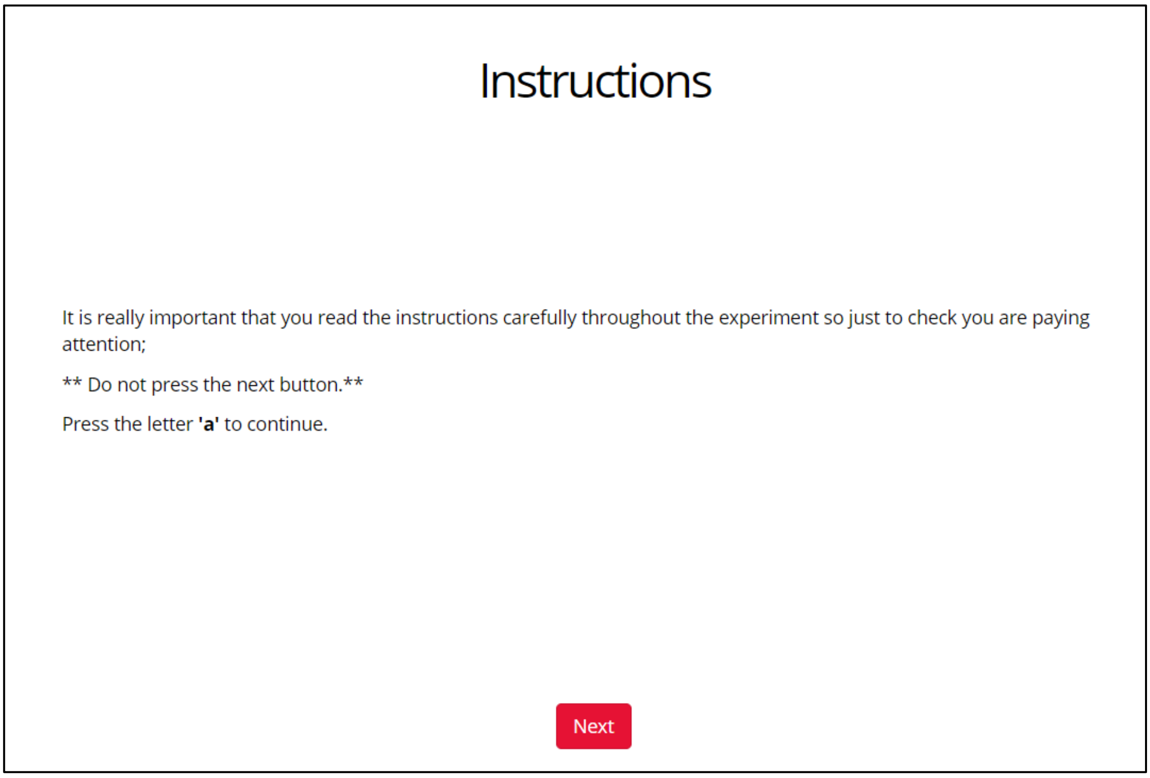
Table 7.1. *Worked example coding for a single trial, taken from Savill et al. (2018) supplementary material.*

Example target list	“teen, quorl, shop, glack, dress, mim”
Target list phonetic transcription[a]	tin kwɔl ʃɒp glæk drɛs mɪm
Lexicality of target items	word, nonword, word, nonword, word, nonword
Example verbal recall response	“teen, bowl, vard, meck, dress, shop”
Response phonetic transcription[a] (where bold=target item, green font=phoneme in correct position, red font=migrated phoneme, black font=non-match)	**tin** bəʊl vɑd mɛk **drɛs** **ʃɒp**
Item response coding	CIP, NON-RECOMB, UNR, RECOMB, CIP, ORD = 2 CIP, 1 ORD, 1 RECOMB, 1 NON-RECOMB & 1 UNR
Tracing lexicality of recalled target phonemes	Correct (CIP) items=7 word phonemes, 0 nonword phonemes ORD errors=3 word phonemes, 0 nonword phonemes RECOMB errors=1 word phoneme (repeated and out of position), 2 nonword phonemes (1 correct and 1 out of position) NON-RECOMB errors=0 word phonemes, 1 nonword phonemes (in correct position)

Note. A. Transcription are shown using the International Phonetic Alphabet for illustration only. Transcriptions used CELEX DISC notation. Key: CIP: Item in correct position. ORD = whole item order errors. RECOMB = responses recombining target phonemes from more than one item. NON-RECOMB = phonologically related errors that did not recombine target phonemes from more than one item: OM = Omissions

Appendix H

Screenshot of the attention check as seen by the participants at the beginning of Chapters 3 to 6.



Instructions

It is really important that you read the instructions carefully throughout the experiment so just to check you are paying attention;

** Do not press the next button.**

Press the letter **'a'** to continue.

Appendix I

Screenshot of a ‘blue dot’ trial, used in Chapters 3 to 6 in immediate serial recall tasks