VERBAL SHORT-TERM MEMORY AND

VOCABULARY LEARNING

by

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Summary

This thesis addressed two key issues. The first was the extent to which verbal short-term memory (STM) for item and order information can be differentiated in terms of their underlying neural mechanisms. The second was to analyze the relative contributions of item and order STM to vocabulary learning in bilingual (BL) and monolingual (ML) children and ML adults.

The first issue was addressed with four studies. Three used electroencephalography (EEG) with ML adults, BL adults and ML children. The aim was to determine whether there is any evidence that the two types of verbal STM have different neural signatures. The fourth study used transcranial magnetic stimulation (TMS) in ML adults to test the hypothesis that the right intraparietal sulcus (IPS) is involved in order STM but not item STM.

The second issue was addressed by two behavioural studies. The first was a large-scale longitudinal study testing item and order STM in relation to natural vocabulary acquisition in 7 to 10 year old BL and ML children. The children were tested once in the beginning and once in the end of the school year. In addition, ML children learning a second language were examined in the end of the school year. The second behavioural study explored therelationship of item and order STM with new-word-learning in ML adults using artificially-created nonwords. Some evidence was found to support the view that the distinction of item and order STM is a useful one.

Results of the EEG data suggested differences in patterns of neuro-electrical activity for ML and BL adults and ML children when they are performing item STM and order STM tasks. The results suggest that order STM is important for new word learning in one´s native language learning, where there has already been some exposure to this language, but not in complete novice language learners.

Declaration

I hereby declare that this thesis has not been submitted, either in the same or different form, to this or any other University for a degree.

Kathrin Angela Maria Mikan

29th of March 2012

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Abstract

Verbal short-term memory (STM) has been shown to be related to the acquisition of vocabulary knowledge in both mono- and bilingual children and adults. Recent studies suggest that verbal STM can be divided into two components: STM memory for serial order and STM memory for item identity information.

This thesis set out to investigate two main questions: The first was to investigate the neural underpinnings of these two components of verbal STM using electroencephalography (EEG) and transcranial magnetic stimulation (TMS) methods. The second was to explore the relationship of item and order STM to vocabulary acquisition at a behavioural level. Throughout the thesis monolingual (ML) English and German speakers and bilingual (BL) German/English speakers were compared at behavioural and neurological levels. This was done to study the influences of language on item and order STM.

The main hypothesis tested in this thesis is that memory for serial order and memory for item identity (a) show distinct neural markers in the brain and (b) make independent contributions to vocabulary acquisition.

Two studies were conducted examining underlying processes of item and serial order STM. In an EEG study with ML adults, ML children and BL adults it was found that item and order STM indeed activate different cortical regions. BL adults, when tested in their second language, show less distinct differences between the tasks. When compared to ML adults they show less positive amplitude in order STM tasks implying they need less cognitive involvement to perform similarly well at this task. The TMS study was designed to determine the role of the intraparietal sulcus (IPS) further, which has been shown to be an important region in verbal STM tasks. Results confirmed the importance of left IPS in both item and order STM but could not endorse the hypothesis of right IPS being more involved in order STM.

A longitudinal behavioural study with ML and BL children investigated the relative importance of item and order STM on native language acquisition. Order but not item STM significantly predicted vocabulary growth within one school year for bilingual children. Item STM correlated with vocabulary acquisition in ML German children but order STM correlated with vocabulary acquisition in ML English children. In addition, BL children outperformed ML children on a test of memory for serial order. These results extend previous research in ML adults and children by examining older children, and children speaking more than one language. The level of language proficiency seems to have an important influence on how item and order STM relate to vocabulary acquisition.

The last study with ML adults investigated the relationship of item and order STM on new-word learning. A novel word-learning task was used to simulate native language acquisition comparing new words that were either based on participant´s native language English (L1) or an unknown language Czech (L2). It was found that order STM (but not item STM) correlated only with L1-type learning but not L2-type learning. Finally, intercorrelations between the different order and item STM tasks used throughout this thesis were calculated. It was revealed that the tasks are somewhat related processes but it is certainly not the case that they are identical in what they are indexing.

The last chapter comprises the general discussion of the results, implications for models of vocabulary learning, suggestions for future work and conclusions. It is argued that the experiments reported in the thesis provide some evidence in support of a distinction between item and order STM but suggest that in the context of vocabulary learning the distinction might only be a useful one in a specific time window with respect to existing vocabulary knowledge, and the relationship between item and order STM and vocabulary acquisition may also vary from language to language.

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Table of Contents

Table of Figures

List of Tables

List of Commonly Used Abbreviations

ANOVA	Analysis of variance
EEG	Electroencephalography
EGI	Electrical Geodesics, Inc (refers to the data analysis and acquisition system)
ERP	Event related potential
fMRI	Functional magnetic resonance imaging
LTM	Long term memory
ML	Monolinguals
PET	Positron emission tomography
STM	Short term memory
rTMS	Repetitive transcranial magnetic stimulation
TMS	Transcranial magnetic stimulation

Chapter 1: Literature Review

1. Introduction

No other creature uses a language as complex in grammar and rich in vocabulary as the human being. What mechanisms allow humans to acquire such a complex language and thus distinguish them from other animals? Apart from physical requirements (i.e. the articulatory system), cognitive processes such as the ability to differentiate sounds [1] (i.e. phonological awareness), memory and attention are required to learn a language.

A large body of research has investigated the relationship between a range of cognitive processes and language learning (e.g., Escribano, 2004; Fearguson & Farwell, 1975; Pulvermüller, 1999; Swain & Lapkin, 1995). One process that research has consistently shown to be critically related to language acquisition (including foreign vocabulary learning) is verbal phonological short term memory (STM), i.e. the capacity for holding a small amount of verbal information actively and readily available in mind for a short period of time. In children and adults, numerous studies have found reliable correlations between measures of vocabulary achievement and indices of verbal STM capacity such as digit span and nonword repetition. These correlations remain after controlling for other possible predictors such as chronological age and nonverbal intelligence (e.g., Gathercole, Service, Hitch, & Martin, 1997; Gathercole, Willis, Emslie, & Baddeley, 1992; Gupta, 2003).

Recent studies have shown that verbal STM can store two distinct types of information: 1) Item identity information, i.e., the phonological, orthographic or semantic properties that define the verbal stimuli being held in STM, and 2) Temporal order information, i.e., the serial position in which each item (i.e. word, letter, or sound) was presented.

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[1] This process is also partly determined by the physical capabilities of the auditory system.

This distinction has been shown at behavioural (Henson, Hartley, Burgess, Hitch, & Flude, 2003; Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009; Majerus, Leclercq, et al., 2009; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008; Mosse & Jarrold, 2007; Poirier & Saint-Aubin, 1996) and neurological levels (Majerus, Belayachi, et al., 2008; Majerus, D'Argembeau, et al., 2009).

2. Verbal STM and Vocabulary Acquisition in Monolinguals

In monolingual (ML) populations, there is a substantial body of behavioural evidence describing a relationship between verbal STM capacity and vocabulary acquisition.

In 1989, Gathercole and Baddeley published a longitudinal study evaluating the role of phonological memory and vocabulary development in 4 to 5 year old children. Phonological memory was investigated by requiring the children to repeat nonwords varying in length and complexity. Children's phonological memory score was highly correlated with their vocabulary at both age 4 and 5. Importantly, phonological memory score at age 4 accounted for a significant amount (30%) of variance in vocabulary score at age 5, followed by nonverbal intelligence which was the second most important predictor.

A follow up study by Gathercole, Willis, Emslie and Baddeley in 1992 looking at the same children aged at age 6 and 8 found a significant shift in the causal underpinnings of the relationship between phonological memory and vocabulary development before and after 5 years of age. Between 4 and 5 years, phonological STM skills appeared to exert a direct causal influence on vocabulary acquisition whereas after the age of 5 current vocabulary knowledge was a stronger predictor of future vocabulary development than phonological STM skills.

In 1999, Gathercole, Service, Hitch, Adams, and Martin investigated phonological STM and vocabulary development in 4 year old children. In their first study they asked whether the link between vocabulary and verbal memory arises from the requirement to articulate memory items at recall or from earlier processes involved in the encoding and storage of verbal material. The children were tested on immediate memory measures which required either spoken recall (nonword repetition, i.e. recall of 2-5 syllable nonwords, and digit span, recalling digit lists of length 2 to 9) or recognition of a sequence of nonwords, as well as vocabulary, articulation rate and non-verbal abilities. The association of phonological memory skills and vocabulary knowledge was found to be as strong for serial recognition as recall-based measures. The results suggested that it was phonological short term memory capacity (nonword repetition, nonword recognition and digit span) rather than speech output skills (articulation rate) which constrain word learning. In a second study, this finding was replicated in teenaged children, indicating that phonological memory constraints on word learning remain significant throughout childhood.

An association between word-learning, nonword repetition, and immediate serial recall has also been found in adults. In two experiments Gupta (2003) measured the performance of 52 monolingual English speaking adults in nonword repetition, immediate serial recall and word-learning tasks. He found that the relationships measured in children between these three abilities also exist in adults. In other words there was a significant correlation between new word learning, nonword repetition and immediate serial recall. A second experiment with 58 adults showed the robustness of these results by using different stimuli and a variant of the word-learning task.

Taken together, the studies described above (and many others, e.g., Avons, Wragg, Cupples, & Lovegrove, 1998; Baddeley, Gathercole, & Papagno, 1998; Bowey, 1996; Gathercole, 1995; Gathercole & Adams, 1993, 1994; Gathercole, Adams, & Hitch, 1994; Gathercole & Baddeley, 1989, 1990, 1993; Gathercole, Service, Hitch, Adams, & Martin, 1999; Gathercole, Willis, & Baddeley, 1991; Gathercole, et al., 1992; Gupta, 2003; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, et al., 2006; Michas & Henry, 1994; Costanza Papagno, Valentine, & Baddeley, 1991; Speciale, Ellis, & Bywater, 2004) suggest that verbal phonological STM is intimately related to language acquisition by showing reliable correlations between measures of verbal STM capacity such as digit span, nonword repetition, and vocabulary achievement after controlling for other possible predictors such as chronological age and nonverbal intelligence.

3. Theoretical Model of Verbal Short-Term Memory and Vocabulary Acquisition

The working memory (WM) model originally proposed by Baddeley and Hitch (1974; see Figure 1) remains the most clearly articulated and extensively investigated theoretical account of verbal STM. The model has been revised several times but originally, the WM model comprised three components: A central executive component and two "slave systems" called the phonological loop and the visuo-spatial sketchpad. According to the model, the phonological loop is used to maintain verbally coded information, and the visuo-spatial sketchpad is involved in the short-term maintenance and manipulation of material that has a strong visual or spatial component. The role of the central executive was always least well described, but amongst its many functions it was assumed to have a role in regulating the flow of information within working memory, the retrieval of information from other memory systems (e.g. long-term memory) and responsibility for the control and regulation of cognitive processes. It was assumed that the central executive is limited in processing resources. Hence the efficiency of the central executive depends on whether other demands are simultaneously placed upon cognitive processing.

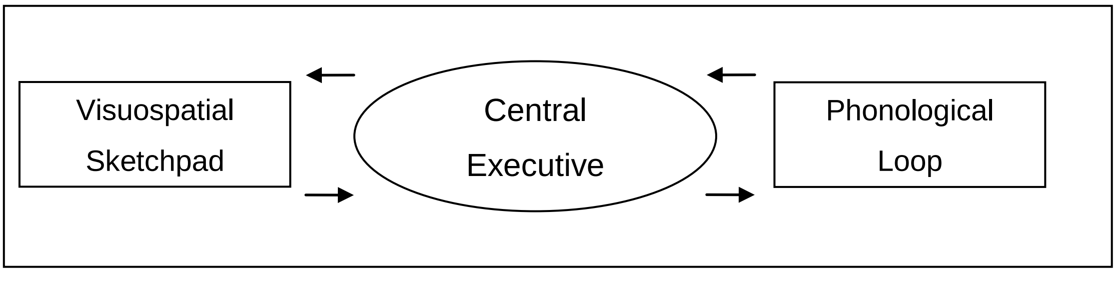

Figure 1: Representation of the Baddeley and Hitch (1974) working memory model

The phonological loop comprises two components, a phonological short-term store and an articulatory rehearsal component. Traces within the store are assumed to decay over a period of about two seconds unless refreshed by rehearsal (Baddeley, 2001). The articulatory rehearsal component serves to refresh the decaying representations in the phonological store and hence to maintain items in verbal STM. In the 37 years since its publication, a very large body of research has developed which supports the concept of the phonological loop (see e.g., Baddeley, 1986; Baddeley, et al., 1998; Burgess & Hitch, 1999 for reviews; Fisk & Warr, 1996), and the phonological loop has proven capable of explaining a great number of experimental findings from normal adult participants, children, and neuropsychological patients (for reviews see Baddeley & Hitch, 1994; Gathercole & Baddeley, 1993).

One such well-established experimental finding is the word length effect, i.e. more short words can be held in STM than long words (Baddeley, Thomson, & Buchanan, 1975; Lovatt, Avons, & Masterson, 2000; Neath, Bireta, & Surprenant, 2003; M. J. Watkins, 1972; Michael J. Watkins & Watkins, 1973). This phenomenon can readily be explained by the working memory model which assumes that short words are better remembered simply because they can be spoken more rapidly – 1.5 seconds of short words will comprise more items than 1.5 seconds of long words (Baddeley, Lewis, & Vallar, 1984).

The concept of the phonological loop can also explain the phonological similarity effect in verbal memory, i.e. why it is much more difficult to recall a set of phonological similar words than to recall a set of phonologically dissimilar words (Conrad & Hull, 1964).

Despite its success, the original WM model could not explain a number of phenomena in verbal learning tasks. For example, it was not able to explain prose recall (recall of a meaningful sentence of up to 16 words is possible while recall of a sequence of unrelated words starts to become difficult after 5 or 6 items) and effects of long-term lexical knowledge on serial recall (recall of words is easier than recall of nonwords) (see e.g., Gupta, 1996; Henson, 1998; Hulme, Maughan, & Brown, 1991).

One problem with the model which prevented it from explaining some of the phenomena in verbal learning tasks was that the model assumed that rehearsal is necessary for performance on immediate serial recall tasks (e.g., participants have to listen to a list of words or digits and recall them immediately afterwards). This is the reason why it also cannot account for the existence of serial recall without rehearsal as seen in patients with neuropsychological impairments (D. Howard & Franklin, 1990) and in children (Gathercole, et al., 1994). As the original model did not have explicit links with long-term memory, it cannot address the effects of item familiarity (Hulme, et al., 1991) or learning phenomena such as the Hebb repetition effect[2] (Hebb, 1961). Another problem for the original model is to explain certain phenomena in STM patients who only have an auditory span of a single item but the ability to recall three or four visually presented items (Shallice & Warrington, 1970). The WM model also does not provide a detailed account of the relationship between immediate serial recall, vocabulary knowledge and nonword repetition abilities (Gathercole & Adams, 1994; Gathercole, et al., 1994). For a detailed discussion about the WM model and its limitations see Baddeley (2000) or Andrade (2001).

To accommodate some of these challenges, Baddeley (2000) proposed a new component of WM – the episodic buffer (see Figure 2). He argued that this component acts as a “back-up store” that can be used to support serial recall (see e.g., Logie, Sala, Wynn, & Baddeley, 2000). The key feature of the episodic buffer is that it is multimodal, e.g. information is not limited to phonological or visual cues. It is able to manipulate, maintain and utilize new information over time. It is assumed to be capable of storing new information in a multi-dimensional code and hence provides a temporary interface between the existing slave systems (phonological loop and visuospatial sketchpad) with access to LTM also being controlled by the central executive. This new component was able to explain some of the findings the model could previously not account for.

2 This effect reflects a phenomenon whereby performance on the immediate serial recall of a list of familiar items is seen to improve over unannounced repetitions of a given list.

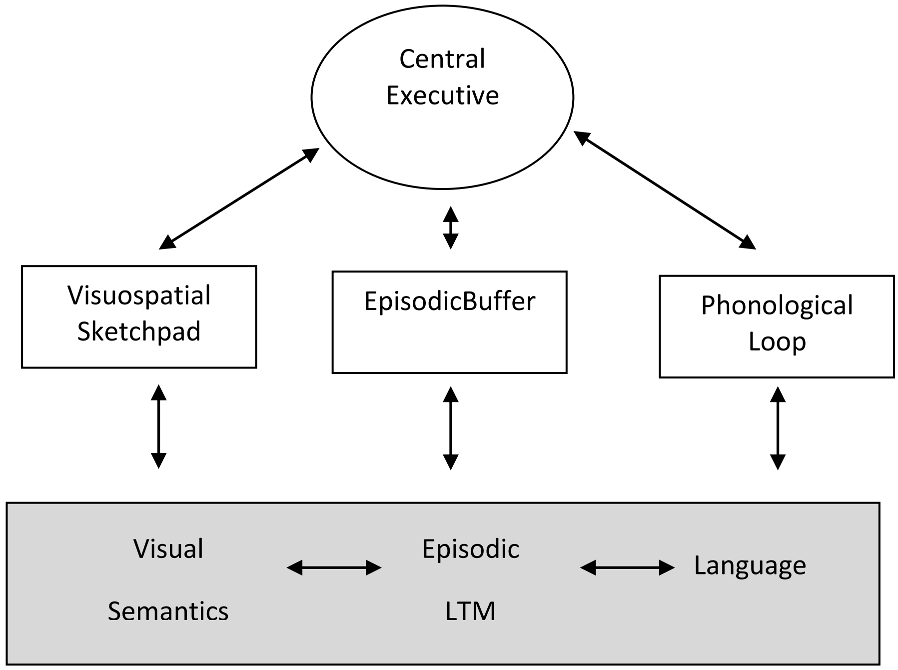

Figure *2:* Revised memory model: Multi-component working memory model by Baddeley (2000). LTM=long-term memory; grey area=crystallized systems; white area=fluid systems

One particularly active and productive area of research has been the role of the phonological loop in vocabulary acquisition. Baddeley, Gathercole and Papagno (1998) propose that the phonological loop evolved primarily for the purpose of temporarily storing unfamiliar sound patterns whilst more permanent memory records are being constructed. They argue that its use in retaining sequences of familiar words might be secondary.

The WM model is one of the most cited and reviewed models of verbal STM. Yet, it was developed before recent evidence of a distinction between item and order components in verbal STM and hence did not accommodate this distinction. The next section provides a review of important findings supporting the distinction of item and order STM and reviews models of verbal STM taking into account item and order STM components.

4. Verbal STM: The Importance of a Critical Distinction of Item and Serial Order Information

As pointed out by Majerus, Poncelet, Elsen, et al. (2006), verbal STM capacity is traditionally measured by immediate serial recall tasks requiring verbal recall of auditorily or visually presented digit, letter or word sequences. Although the instructions for these tasks appear quite simple, recalling lists of multiple verbal items can indeed be a very challenging task. Recent studies have suggested that a critical distinction can be made between two types of information that are retained in verbal STM: 1) item identity information and 2) temporal order information. Item information is the phonological, orthographic or semantic properties that define the verbal stimulus while order information includes the serial position in which each word or letter was presented. These two types of information are frequently confounded in studies on verbal STM, yet their distinction may be fundamental for understanding verbal STM and its relationship to new word learning capacities.

In the following sections, recent models of verbal STM that assume that the coding for serial order and the coding for item information in STM are at least partially distinct will be discussed (e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999; Gupta, 2003; Gupta & MacWhinney, 1997; Henson, 1998; Lee & Estes, 1981). These models all contain some form of external signalling mechanism ensuring the encoding of serial order information, while the items on which this signalling mechanism operates are represented directly. The review of recent models is then followed by an extensive summary of empirical evidence supporting separate STM codes for item and serial order information in behavioural, neuropsychological and neuroimaging studies.

It should be noted that it is hard to design tasks that only capture either verbal order or item STM distinctly. In the typical order STM the serial position of specific stimuli material (e.g. words, letters, pictures, etc.) has to be remembered, while in the typical item STM task, the item identity (e.g. phonological, orthographic or semantic properties of specific stimuli material) also has to be remembered. The question of an order task could hence be: “Was stimulus X in position Y?” and in an item task the question might be: “Did stimulus X occur in the list at all?” Thus, in tasks that measure order STM it is impossible to completely eliminate retention requirements for item information. For example, when remembering if stimulus X was in position Y, the phonological/orthographic/semantic information associated with that stimulus will most likely also be remembered together with the position. In a study by (Neath, 1997) it was shown that variables that usually affect item recall, such as concreteness, also affect serial order reconstruction tasks. Similarly, for item STM tasks, order retention requirements cannot be completely abolished given that retention of order information (i.e. at the phoneme level if words are used) is necessary in order to encode the word. It is, however, possible to design tasks where item and order STM components of verbal STM are maximized respectively, i.e. in the serial order tasks retention requirements for serial order can be maximized whereas requirements for processing of phonological item information can be minimized. The opposite is true for the item STM tasks. This is the approach adopted in the experiments reported in this thesis.

5. Verbal STM Models of Item and Order in Relation to Vocabulary Acquisition

The Working Memory model previously introduced in this thesis (Baddeley, 2001; Baddeley & Hitch, 1974) did not make a distinction between item and order verbal STM but rather tried to explain vocabulary acquisition on the basis of the properties of the phonological loop. However, in recent years models of verbal STM have been developed that are directly linked to vocabulary acquisition and also make a distinction between item and order verbal STM. These will be outlined below.

The perturbation model of Estes (1972; see also Lee & Estes, 1981; Nairne, 1991; Nairne & Kelley, 2004) makes a distinction between memory for an item`s occurrence on a particular trial and memory for its serial position within the trial: According to this model, a typical memory experiment can be represented in three dimensions, [i], [j], [k] (see Nairne, 1991). Variable [i] maps the order of lists as presented, variable [j] the order of subjective groupings within a list, and variable [k] the position of the item within a group. An item might hence be coded as having occurred in the third serial position (i.e., within list dimension – variable [k]) in the fourth list of the session (i.e., list dimension – variable [j]). It is then assumed that these representations drift or "perturb" along the encoding dimensions over time (see Estes, 1972; and Nairne, Riegler, & Serra, 1991 for details). An order error is created when an item drifts with a certain probability into an adjacent position in the list. For example, an item that was presented originally in position 3 is now remembered as having occurred in position 2 or 4. Item errors are created when drifting occurs within a list. Another possibility is that an item will perturb into a different list, leading to an omission – or item – error at the point of recall. In this way it is possible to retain accurate memory for an item within list position (order information), but fail to recall the item itself (item information). The loss of item, but not order, information occurs because the item is remembered as having occurred on a different trial. For correct order recall, it is important to remember both the item and the within list position in which it occurred.

In 1998, Henson developed a connectionist model of STM he called the Start-End-Model (SEM). The model was designed to address the question of how a novel sequence of items can be stored and retrieved from STM in the correct order. Henson`s model is based on three earlier theories of how order is retained in memory (for a review see Henson, 1998, 2001): The chaining theory(Ebbinghaus, 1885) assumes that serial order is stored by a "chain" of associations between successive items (see Figure 3: A). Only pair-wise associations between successive items are assumed in simple chaining models: Each item in a list cues the recall of its successor (chaining). Positional theory (Conrad, 1965) assumes that each item is simply coded for its position in the sequence. Conrad (1965) argued for example, that in a list learning task, each item is stored in a separate "box" in memory, and that order is retrieved by stepping through the boxes in a predetermined routine (see Figure 3: B). Finally, ordinal theory (e.g., Page & Norris, 1998) assumes that order is represented by the relative values of some continuous property of the items (see Figure 3: C). The first item is the “strongest” and the last item the “weakest”. The order of items is retrieved by an iterative process of selecting the strongest item and then temporarily suppressing it so as to recall the next strongest item in the list and so on (Grossberg, 1978).

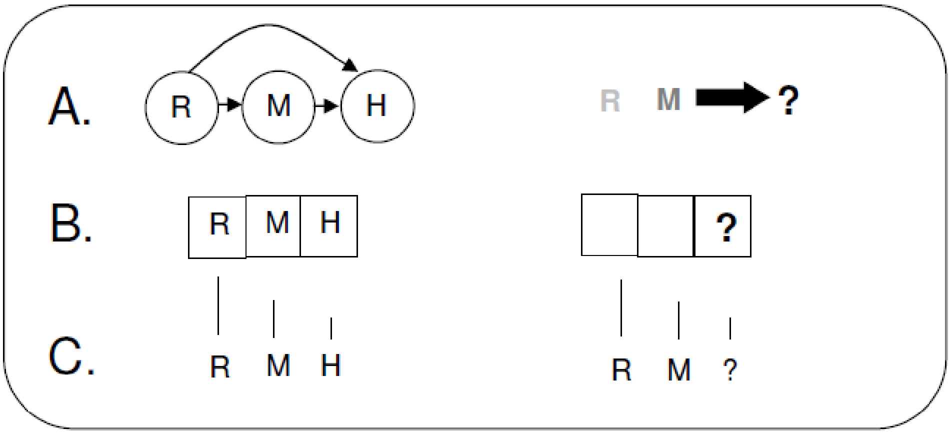

Figure 3: Example of (A) chaining, (B) positional, and (C) ordinal models of serial order (Figure adapted from Henson, 2001)

Elements of each of these theories are integrated in the computational SEM model from Henson (2001). The model assumes that the order of events is encoded by associating each to-be-remembered event with its position in a sequence. It is further assumed that positions of items in a sequence are coded relative to the start and the end of a sequence (hence the name Start-End-Model). When an event is encoded, at every rehearsal of an item including recall an “episodic token” is created in STM – each token contains components that represent item information and position information separately. The positional context information is provided by a start marker and an end marker whose strengths decrease and increase respectively across list positions – hence the strengths of the start and end marker define a unique list position and those strengths are stored together with the list item. Importantly, the item is recorded in its output position (i.e. a correct or incorrect response) and the general context of the new token is updated to the current context – in other words, the continual updating of contextual information in this model corresponds to maintenance rehearsal in STM.

The model makes three key assumptions: (1) the start and end of a sequence are the most salient aspects of a sequence and provide potential reference points or anchors, to which the elements of the sequence can be ordered. Hence, SEM's coding of position presumes a start and end marker with the start marker being strongest at the beginning of a sequence and then decreasing in strength towards the end of the sequence. The end marker on the other hand is weakest at the start and grows in strength towards the end of the sequence. This relationship provides an approximate two-dimensional code for each position in a sequence (Coding of position). (2) Each occurrence of an item is assumed to create a new token in short-term memory that represents an episodic record of a particular item occurring in a particular spatiotemporal context (Position-sensitive tokens). STM is hence seen as a set of new, episodic tokens. Tokens contain several components such as item identity information or positional information. The last assumption of the SEM is that (3) tokens in STM are unordered and hence their ordering occurs during recall. To recall a sequence in its correct order the SEM cues each response by reinstating the positional code of the position that is recalled. Once an item has been recalled, its representation is temporarily suppressed which reduces the probability of recalling an item more than once within the same trial. This assumption is also common to other models of serial recall (e.g., Burgess & Hitch, 1992) and in fact Henson argues that the SEM can be mapped onto Baddeley and Hitch's working memory model by assuming that its transient phonological activations correspond to Baddeley`s phonological store and that its rehearsal process corresponds to Baddeley`s articulatory control process.

The SEM can explain phenomena in serial recall such as the effects of primacy and recency (first and last words of a list can be remembered better than the words in the middle), list length, and phonological similarity. It also captures the pattern of errors typically observed in list learning such as transpositions, repetitions, omissions, intrusions, confusions and positional errors between groups and trials (Henson, 1998, 2001).

A different approach to explaining the effects of serial order (i.e. that recall accuracy varies as a function of an item's position within a study list) is provided by Burgess and Hitch (1999, 2006; see also Hitch, Flude, & Burgess, 2009) who described a connectionist model that builds on the insights of the phonological loop component of Baddeley (1986) and extended it to encompass serial order and learning. The model comprises two main components, a phonological/lexical store for item information (represented by the “item” box in Figure 4) and a context-timing signal that encodes the serial order of items (represented by the “context/timing” box in Figure 4). Phonological, lexical and timing information are represented in separate layers of nodes and each node can transmit activation to nodes in adjacent layers according to the strengths of connections between them. Learning and forgetting occurs through increases and decreases in the strengths of modifiable connections. The model assumes separate speech input and output systems during verbal learning, which are connected by two pathways. One pathway leads via an item representation and ordering mechanism towards the speech output and a second pathway connects the input and output levels directly.

According to the model, recall of each item is a two-stage process in which the first stage involves processing serial order information and the second stage involves processing phonological information. Presentation of an item activates its node in the item layer and triggers a learning process whereby connections between simultaneously active nodes in adjacent layers are strengthened. The activation of nodes in the context/timing layer changes continuously over time (both short- and long term) such that patterns of activation at adjacent time-steps overlap (see also Burgess, 1995; Henson & Burgess, 1997). As a result, the order of items is encoded in the form of position-item associations. In addition, presentation of an item strengthens item-phoneme and phoneme-item connections (see Figure 4 for a simplified structure of the model).

Key features of this model are that mathematically defined long- and short-term connection weights explain Hebbian learning, i.e. recall performance improves if a list has recently been presented and recalled (Hebb, 1961). Reciprocal connections between the two phoneme layers (input and output) include information about the presentation modality and familiarity of items. Within this model, the sounds of new words and their pronunciation are learned by strengthening connections between phonological and item representations, whereas memory for serial order (which is crucial for people`s every day functioning such as interpreting auditory stimuli and in using language) can be improved by strengthening connections between items and context/timing representations. The context signal is entrained by the temporal organisation of the stimuli. Associations to the context signal are responsible for effects of both temporal grouping of stimuli and long-term learning of their serial order. Due to its complex features, the model is able to explain serial position effects, effects of presentation modality, lexicality (performance is better for nonwords that resemble known words than for those that do not), grouping (grouped items are remembered better) and Hebb repetition effects. Crucially, Burgess and Hitch (1999) contend that their model is a basis for understanding the role of the phonological loop in vocabulary acquisition. It was the first model to make an explicit connection between memory for serial order and new word learning.

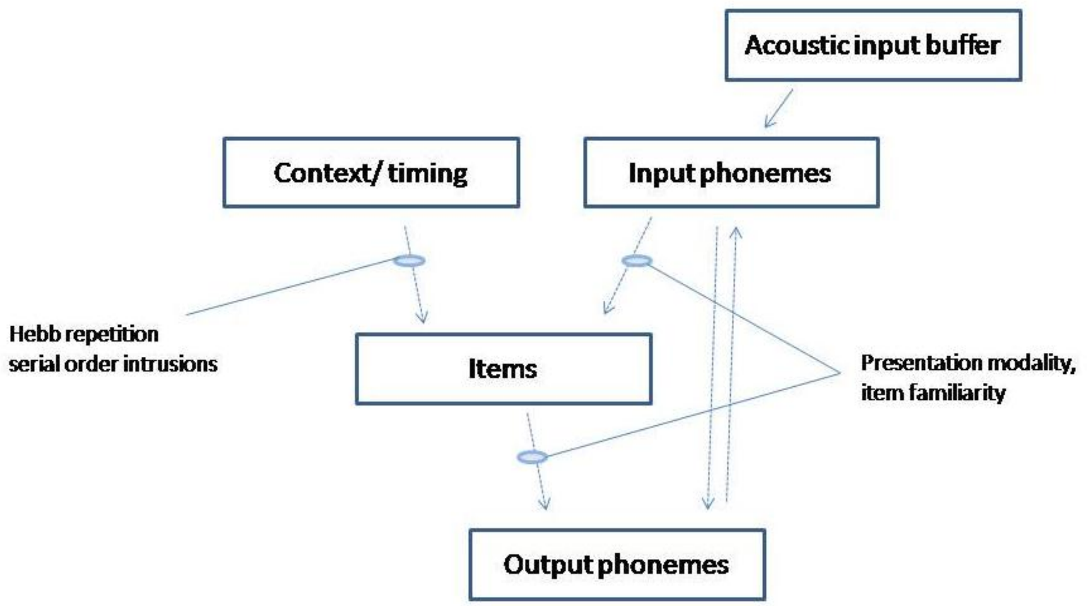

Figure 4: Simplified structure of Burgess and Hitch's model (1999); Boxes denote layers of nodes; the text inside the boxes indicates what the nodes represent.

Another model that makes a clear distinction between item and order STM was developed by Gupta (Gupta, 2003; Gupta & MacWhinney, 1997). This computational model was designed to explain the relationship between verbal STM and language processing. The model comprises three levels of representation: A phoneme layer (level of output phonology at which phonemes are represented), a phonological chunk layer (in which word forms are represented for both input and output phonology) and a semantics/context layer (which represents semantic/contextual information about word forms). These levels are related to each other via connection weights. According to the model, the production of a word form is a serially ordered process and therefore, the representation of a word form at the Phonological Chunk Layer has to be able to produce a specific sequence of phonemes at the Phoneme Layer. A general sequencing mechanism provides immediate memory for sequences of novel word forms (i.e. it can replay a sequence of activations that have occurred recently at the Phonological Chunk Layer).Including this mechanism allows the model to simulate repetition of novel word forms, the learning of novel word forms and serial recall of lists of known word forms. Gupta (2003) suggested that the probability of creating a stable representation in the word form system for a new word form will be greater when serial order information encoded in STM can accurately reactivate the corresponding phoneme sequence in the sublexical language network during the learning process. Gupta’s model generates an explicit prediction about the nature of the relationship between memory for serial order and vocabulary acquisition by suggesting that the probability of creating a stable representation in the word form system for a new word form will be greater when serial order information encoded in STM can accurately reactivate the corresponding phoneme sequence in the sublexical language network during the learning process (Gupta, 2003).

A model that explicitly links memory for serial order information with new word learning was developed by Botvinick and Plaut (2006). According to their model, sequence information is encoded through sustained patterns of activation within a recurrent neural network architecture. Recurrent connections make sure that the neuronal network connection strengths are not only calculated out of given inputs, but that they are influenced via feedback from previous conditions of the network connection strengths. Although the model does not explicitly operate through a chaining mechanism, it does respond to consistent sequential relationships among the items to which it is exposed. Botvinick and Plaut (2006) claim that a basic difference between their model and context-based accounts[3] such as Brown, et al., (2000), Henson (1998) or Burgess and Hitch (1999) involves the distinction between activation-based and weight-based forms of short-term memory. The context-based framework is dependent on transient, trial-specific links between item and context representations while in the Botvinick and Plaut model connection weights do not change during a single trial. Another difference to context-based models is that these assume separate and independent representations of item and position information (i.e. context or timing) whereas Botvinick and Plaut's model represents item and position conjunctively within a single distributed representation. The distinction between conjunctive versus independent representations of item and position in context based models has often been linked to the claim that serial recall involves a two stage process: a first stage where position information is retrieved and a second stage at which item identification occurs (see e.g., Henson, 1998). Botvinick and Plaut's model learned to process the serial order of letter strings, nonwords and also artificial grammar successfully. However, it did not make a specific prediction about the relationship between item versus order component memory processes in verbal STM and vocabulary acquisition.

Brown, Vousden, McCormack and Hulme's (1999) application of the OSCAR model (Oscillator-based Associative Recall: Brown, et al., 2000) also highlights the importance of memory for serial order in the development of verbal learning. In the OSCAR model, an array of oscillators (i.e. different mathematically based frequencies) is used to provide the dynamic learning-context signal to which successive items in a sequence become associated.

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[3] The majority of context-based models (Burgess & Hitch, 1999; Henson, 1998) have been presented in the form of neural networks where the associative links between item and context representations are established by changing the connection weights between processing units. Context-based account can thus be characterized as using a weight-based method for encoding and maintaining serial order information, a point that strongly differentiates it from the activation-based framework (Botvinick & Plaut, 2006).

The authors assume that the development of serial order ability results from age-related changes in a dynamic learning-context signal, or in other words when applied to a developmental context it simply means that less accurate (i.e., less temporally distinctive) retrieval cues are available to younger children, leading to more order errors and slower retrieval. Their model is able to correctly predict developmental changes in the error patterns in children's serial order recall and suggests that the development of memory for serial order is due to increases in the temporal distinctiveness of item identity representations in memory that emerge with age and experience. This model was the first to assume independent mechanisms for item and order memory in children's verbal STM and attempt to explain different patterns of performance for each memory component in language development.

Majerus (2008) also presented a model of verbal STM (see Figure 5) that attempts to explain the relationship between verbal STM processes and language learning. He differentiates between STM processes that support item and serial order information. The model includes a language system which contains a sub-lexical network of phonological, lexical and semantic representations, which are used to process verbal "item information". An additional system is used for the processing of serial order information. The systems are linked by a higher level attentional system similar to the central executive component of Baddeley and Hitch's model (1974). Dependent on task demands, this system allocates limited processing resources to the sub-systems involved in encoding, maintenance and repetition of items as well as the language system. It can be seen from this model that any relationships between memory for serial order and vocabulary learning may depend on the capacity of the attentional system. In other words, although there are clearly independent components in verbal STM that contribute to vocabulary acquisition, as in the other models described above, the components of memory for serial order, item memory and LTM for extant vocabulary each depend on attention for successful learning. For a graphic depiction of the model see Figure 5.

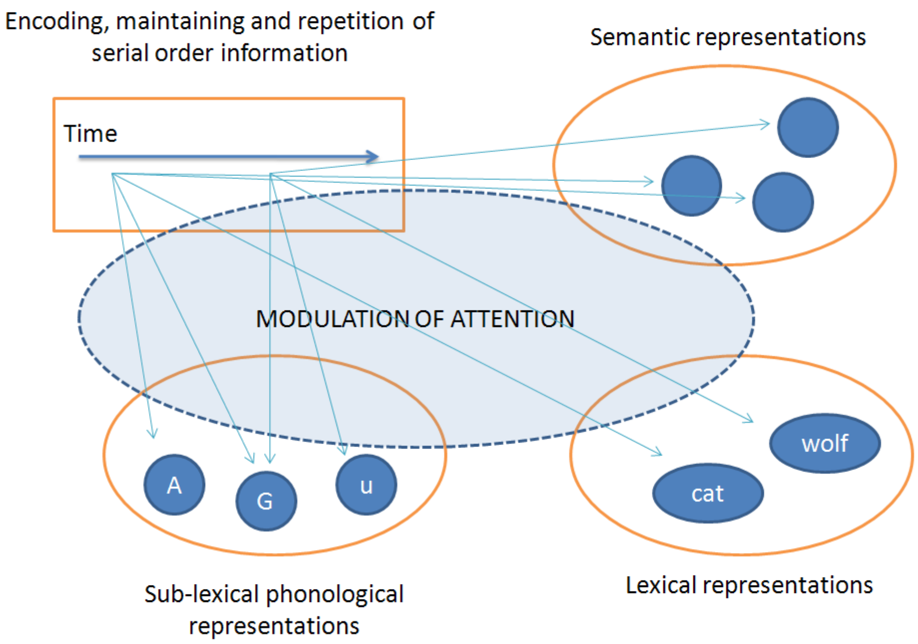

Figure 5: Model of item and order information according to Majerus (2008)

From the review of models above it can be taken that models that make an explicit distinction between memory for serial order and memory for items and their relationship to vocabulary acquisition in children and adults (such as the ones by Brown et al., 1999, and Majerus, 2008) typically assume the following: While order STM is directly related to the process of new word learning (and might even be a language-independent process), item STM capacity reflects the structure of the language network and hence is a constraint on new word learning (as item representations are supposed to be encoded via temporary activation of the language network, e.g. Gupta, 2003; Gupta & MacWhinney, 1997). According to these accounts memory for item identity will necessarily depend more on age and experience than memory for serial order, as LTM for vocabulary will change over time whereas order STM seems be more vocabulary independent. Some models that distinguish between memory for items and memory for order also allow for a different developmental trajectory with respect to the relative importance of each component in vocabulary acquisition (e.g., Majerus, 2008).

6. Item and Order STM – Evidence from Behavioural Data in Monolinguals

In 1996, Poirier and Saint-Aubin found that manipulating the phonological properties of lists of to-be-recalled words had differential effects on item information and serial order recall in an immediate serial recall task (i.e., recalling stimuli in their correct serial positions). The to-be-recalled lists consisted of either high, medium, or low-frequency items and were made out of either phonologically similar or distinct items. Increasing word frequency enhanced item information recall only, but had no effect on order recall. Increasing phonological similarity on the other hand, had a detrimental effect on order recall but no significant effect on item recall.

Henson, Hartley, Burgess, Hitch and Flude (2003) tested a new paradigm comparing an “item probe” task, requiring memory for items, with a “list probe” task, requiring memory for serial order. The serial order probe recognition task comprised a sequential presentation of a list of letters, followed by the simultaneous presentation of a new list containing the same letters. The second list was either identical to the one before or it only differed by the inversion of two adjacent items. For the item probe recognition task, a list of letters was presented sequentially and was followed by a single probe item that either was or was not part of the list. The authors showed that articulatory suppression and the presence of irrelevant speech during the tasks had a greater detrimental effect on the serial order probe recognition task than on the item probe recognition task.

Nairne and Kelley (2004) report four experiments adapting the process dissociation procedure developed by Jacoby (1991) to dissociate item and serial order recall in an immediate serial recall task. Originally the process dissociation procedure had been devised to dissociate automatic and controlled processes in LTM retrieval by assuming that both automatic and controlled processes contribute to performance and operate independently. This might also be the case for item and serial order information in STM tasks. The procedure comprises two different recall conditions: In one condition, participants were instructed to recall items in their correct serial position. This was called the inclusion condition and tapped both item and serial order recall. The authors point out that when independence between item and order recall is assumed resulting performance should be the product of the probability of remembering the item (I) multiplied by the probability that its ordered position is remembered (Or). In the second condition, the exclusion condition, participants were instructed to recall any item except the item that occurred in position X. Nairne and Kelley (2004) assumed that the item that occurred in position X would be recalled (with probability I) only if its serial position had been forgotten (with probability I-Or). Solving of the resulting equations (inclusion = I*Or; exclusion = I[1-Or]) hence provided the authors with estimates of item and order recall. I is the sum of performances in the inclusion and exclusion conditions; Or is obtained by dividing inclusion performance by I.

In Experiment 1 phonological similarity was manipulated across Inclusion and Exclusion conditions as phonological similarity is widely believed to impair order retention, as evidenced by serial recall and reconstruction performance (see Baddeley, 1966; Conrad, 1964), but to increase retention for item information (see Michael J. Watkins, Watkins, & Crowder, 1974). They found that phonological similarity led to increases in the estimates of item information and to decreases in the estimates of order information. The authors point out that this phonological similarity effect is viewed as a bench-mark finding in the immediate memory literature and that virtually all models of serial order include mechanisms to account for the effect (Baddeley, 1986; Burgess & Hitch, 1999; Henson, 1998; Lee & Estes, 1981; Nairne, 1990; Page & Norris, 1998). However, the detrimental effect tends to be restricted to order recall - when the task is free recall then phonological similarity has been found to lead to a beneficial effect (Michael J. Watkins, et al., 1974; Wickelgren, 1965). Hence it has been concluded that phonological similarity has opposite effects on item and order retention, improving item memory and impairing order memory. Nairne and Kelley (2004) also point out, that of course this conclusion rests on a dubious link between task and process as neither serial recall nor free recall is process pure with respect to item and order information. In their second experiment, Nairne and Kelley compared the effects of semantic similarity on item and order STM. Like phonological similarity, semantic similarity has also been found to have differential effects on item and order memory (see e.g., Crowder, 1979; Murdock, 1976; but also see Saint-Aubin & Poirier, 1999a). In this experiment lists were constructed based on semantic, rather than phonological similarity. No similarity decrement was found but as with other researchers (Saint-Aubin & Poirier, 1999b) a similarity advantage in immediate serial recall was found which can be attributed to enhanced item memory.

Experiment 3 and 4 investigated word frequency and generation respectively. It has previously been argued that in immediate serial recall high frequency words generally lead to superior performance (see e.g. Hulme, et al., 1991; Poirier & Saint-Aubin, 1996). The argument here is that people are better able to interpret the traces of high-frequency words because they have richer associations in long-term memory, or phonological representations that are easier to access in lexical memory[4]. Stimulus materials consisted of words four to seven letters in length. Within each block, half of the lists contained five unique high frequency words and half contained five unique low frequency words. A highly significant effect of frequency was found with high frequent words leading to superior serial recall performance. However, frequency exerted its main effect on omission errors (forgetting to recall an item) as significantly more omission errors occurred in the low-frequency word lists. The authors argue that this finding supports the claim that frequency affects primarily item rather than order retention.

6.1. Studies on Item and Order STM and Vocabulary Acquisition

Some studies have looked specifically at the impact of individual differences in item and order information components in verbal STM on vocabulary

[4]Note that this could automatically lead to bilinguals showing better serial order performance, especially if they know two similar languages such as English and German (both Germanic languages) as similar words might results in richer associations not only between words but also between languages.

acquisition. In a developmental study with monolingual French speaking children, Majerus, Poncelet, Greffe, et al. (2006) showed that STM for serial order and item information follow different developmental trajectories and are differentially related to vocabulary development. Memory for serial order was assessed using a serial order reconstruction task and memory for item identity was assessed with a rhyme probe recognition task. In the order memory task, children listened to lists of three to nine digits (excluding 0). After the presentation of the sequence the children were given cards on which the digits presented during the trial were printed and were asked to put the cards in the order of presentation. In the item memory task participants listened to lists of words (two to seven items) followed by a probe word and had to judge whether the probe words rhymed with one of the words in the list or not. In 4-year-olds and 6-year-olds, only order STM and not item STM was significantly related to vocabulary knowledge but in 5-year-olds only item STM and not order STM was significantly related to vocabulary knowledge. Majerus, Poncelet, Greffe, et al. (2006) proposed a causal association between memory for serial order STM processes and vocabulary development and moreover that memory for serial order and memory for item identity follow different developmental trajectories in their relationship with monolingual vocabulary acquisition.

Majerus, Poncelet, Elsen, et al. (2006) replicated this dissociation between STM for item and serial order information in a sample of adult participants. In the first part of the study, the relationships between STM for serial order, item recall and item recognition were investigated. Order STM was tested with a serial order reconstruction task (as described above), where participants knew the items in advance (always the digits 1 to 9), minimizing STM for item information. Two tasks were developed to maximize STM for item information. One was an immediate serial recall task, measuring recall for both serial order and item information. Here, word lists of increasing length were presented and the participants had to recall the words in their correct serial position. Item and order errors were measured. The second task designed to measure item information STM was a rhyme probe task (as described above). Interesting results were found: Only the serial order reconstruction task correlated with the number of order errors in the immediate serial recall task, whereas only the rhyme probe recognition task correlated with the proportion of item errors in the immediate serial recall task. In a second part of the study, the authors investigated the relationship between new word learning, serial order recall, item recall, and item recognition. New word learning was assessed by requiring participants to learn a series of word-nonword pairs. The authors observed a stronger correlation between novel word learning capacities and the STM task maximizing recall of serial order information; compared to novel word learning capacities and the STM task maximizing recall of phonological item information.

Jefferies, Frankish and Ralph (2006) investigated lexical and semantic influences on item and order memory in immediate serial recognition. It had previously been argued that lexical/semantic effects in verbal STM arise during a redintegrative process (the restoration of the whole from a part of it) at recall. This argument was based on studies that failed to find effects of lexical and semantic factors in matching span tasks (see e.g., Gathercole, Pickering, Hall, & Peaker, 2001; Knott, Patterson, & Hodges, 2000; Thorn & Gathercole, 1999; Thorn, Gathercole, & Frankish, 2002; Walker & Hulme, 1999). Jefferies et al. (2006) suggested that the traditional matching span task is insensitive to lexical/semantic effects because it primarily measures memory for item order, whereas lexical-semantic knowledge largely affects memory for item identity. The authors tested their theory by comparing performance on a traditional matching span task, which required changes in item order to be detected (participants listened to auditorily presented 5-item lists and had to decide whether the lists had been identical or different), with a novel matching span task that required changes in phoneme order - and consequently item identity - to be detected (similar to the first task but including nonwords and words instead of only words). Lexicality, frequency and imageability affected matching span performance but the standard matching span task was relatively insensitive to lexical/semantic factors. Hence they are consistent with previous research showing that lexical/semantic factors reduce the frequency of item identity but not order errors in immediate serial recall (Gathercole & Baddeley, 1989; Hulme, et al., 1997; Poirier & Saint-Aubin, 1995, 1996; Saint-Aubin & Poirier, 1999a, 1999b, 2000; Walker & Hulme, 1999).

In a further study, Majerus, Heiligenstein, et al. (2009) investigated the impact of auditory selective attention on verbal short-term memory and vocabulary development in French monolingual children. They assumed that auditory selective attention capacities are a possible mediator of the association between verbal STM and vocabulary development. Forty-seven 6 and 7 year-old monolingual children were administered two tasks: In the verbal STM task, children listened to a list of two to six animal names and were asked to recall the animals in their correct order. The task was then analysed for item and order errors to determine individual STM scores. Item errors were omissions and confusions (i.e., an animal not presented has been selected) order errors were if a target animal was recalled in the wrong serial position. In the auditory selective attention task for items and sequences, the participants needed to detect target auditory items and target auditory sequences, respectively. The auditory stimuli were sampled from the same animal name recordings as those used in the serial recall task. Picture representations of the two or three target animals were displayed on a computer screen throughout the entire task to permanently cue the target stimuli and to minimize STM load as much as possible. In the item selective attention condition (targeting auditory items) participants listened to an auditory stimulus stream and were asked to press a response button as quickly as possible when they detected a target stimulus.

For the sequence selective attention condition (targeting auditory sequences) the task design was quite similar, with the exception that the picture representations of the target stimuli on the computer screen were spatially organized from the top left corner to the bottom right corner to signal their sequential organization. The children were asked to detect the target sequence in the auditory stimulus stream, starting with the animal displayed at the highest and most left-ward position and finishing with the lowest and most rightward positioned animal. In this way, both tasks probed the processing of item and serial order information independently. It was found that the order but not item recall STM measures (i.e., order errors in the verbal STM task) was independently correlated with vocabulary development as measured by the EVIP scales (a French adaptation of the Peabody Picture Vocabulary Test measuring receptive vocabulary knowledge). This association became non-significant when sequence, but not item selective attentional capacities were partialled out. In addition, the relationship between sequence selective attention and vocabulary knowledge became non-significant after controlling for item selective attentional capacities. Hence, two variables were found to determine vocabulary knowledge: (a) a serial order processing variable shared by STM order recall and the selective attention task and (b) an attentional variable shared by selective attention tasks. On the basis of these findings, the authors argue for the need for integrative STM models, which can account for conjoined influences of attentional capacities and serial order processing capacities on STM performance. They point out that recent theoretical models of verbal STM consider that the ability to temporarily store sequence information allows the reactivation and the ordered replay of a new unfamiliar phonological sequence, increasing the probability that this temporary verbal information is eventually transformed into a more stable long-term representation (e.g., Burgess & Hitch, 1999; Burgess & Hitch, 2006; Gupta, 2003). The storage of item information, on the other hand, is considered to rely mainly on temporary activation of the language system, and in that sense it recruits language knowledge rather than serial order STM mechanisms.

In 2010, Leclercq and Majerus published a longitudinal study which found that serial-order STM, but not item STM, predicted vocabulary development in 4 to 5 year old monolingual French-speaking kindergarten children. Serial order memory was measured by a serial-order reconstruction task adapted from Majerus, Poncelet, Greffe, and Van der Linden (2006): auditory sequences of animal names, increasing in list length, were presented and the child had to reconstruct the order of presentation of the animal names using cards depicting the animals. Item STM was assessed using a single nonword delayed repetition task designed to maximize the recruitment of sublexical phonological representations and segmentation processes. These processes are assumed to be a major determinant of phonological item STM according to theoretical models (see Section 5 in this chapter). Children listened to a nonword and then had to repeat the syllable *bla* for 3 seconds and afterwards had to recall the nonword. Receptive vocabulary knowledge and nonverbal reasoning skills were also considered. At age 4 and at age 5 serial order STM capacities but not item

STM capacities, were specifically associated with vocabulary knowledge. This was also found for children from age 4 to age 5 (in children aged 4, order STM capacities but not item STM capacities predicted vocabulary knowledge one year later at age 5). The increase of serial-order STM capacity from age 4 to age 5 predicted the increase of vocabulary knowledge over the same time period. The authors argue that their results support a theoretical position that assumes an important role for serial-order STM capacities in vocabulary acquisition.

7. The Relevance of Data from Bilingual Participants on the Relationship of Item and Order STM and New Language Learning

This final section considers the potential for studies using bilingual participants to inform our understanding of the relationship between verbal STM, vocabulary acquisition and the importance on differentiating between item and serial order information in verbal STM. To learn a language, physical requirements (i.e. the articulatory system) and cognitive processes (such as the ability to differentiate sounds - i.e. phonological awareness, memory and attention) are required. These processes not only enable humans to acquire the language that is native in their environment but also (uniquely) to become bilingual or even multilingual speakers – that is learning to use more than one language in different environments.

The majority of people in the world are bilingual (see e.g., Grosjean, 1982; Lewis, 1976; Romaine, 1995) and hence it is important and desirable to learn more about bi-(or even multi-)lingualism. One of the biggest difficulties in this area is in defining exactly what is meant by bilingualism.

It is traditional in bilingual research to categorize speakers as being either *balanced bilinguals* (Lambert, Havelka, & Gardner, 1959), *dominant bilinguals* and *passive or recessive bilinguals*. Lambert et al. (1959) first described balanced bilinguals as individuals who are fully competent in both languages. However, Fishman (1972) and Baetens-Beardsmore (1982) argued that bilinguals are rarely equally fluent and that even high-level conference interpreters tend to have a preference for one of their languages. *Dominant bilingual* refers to individuals who are dominant in one language and the other language is often referred to as the subordinate language. However, Chin and Wigglesworth (2007) point out that the term ‘dominance’ might not apply to all domains as individuals might use different languages in different areas or on special topics. *Passive or recessive* bilinguals are a) individuals who are losing competence in one language, mainly because of disuse or b) individuals who have the ability to understand but not produce language in their second language. Individuals who have limited level of proficiency in both their first and second language, are called *semilinguals* (Hansegard, 1975, p. 8; as cited in Skutnabb-Kangas, 1981, p. 253) or ‘limited bilinguals’ (Cummins, 1994).

Annick De Houwer (2005) talks about a ‘double acquisition process’ in children who acquire two languages from birth, where two morphosyntactic systems are acquired as fundamentally separate and closed systems. She further states that so far, no evidence has been found of systematic morphosyntactic influence from one language on the other in children who have been acquiring two languages simultaneously, also there is no evidence that hearing two languages from birth leads to language delay.

An additional complicating factor in bilingual research concerns the nature of the languages spoken. I.e. speaking English and German, both Germanic languages with alphabetic script that share many cognates (words that are identical or similar in the two languages, such as arm/Arm or rose/Rose), show different cognitive processes than bilinguals speaking English and Mandarin Chinese, with Mandarin using morphosyllabic characters and being a tonal language differing considerably from English (see e.g., Saalbach & Stern, 2004).

Despite these definitional difficulties, research into bilingualism is an active area that has made many important contributions: Research with bilinguals not only produces practical findings, such as how to learn a second language best or how language learning intersects with academic achievement, but also theoretical findings such as models of language acquisition, language processing and language influences on other skills such as memory or attention.

In the following section, specific studies with bilingual and multilingual participants will be reviewed, first describing general research of verbal STM and vocabulary acquisition in bilinguals, followed by empirical evidence supporting separate STM codes for item and serial order information also in bilingual population.

Service (1992) found that repetition accuracy for English pseudo-words was a good predictor of English vocabulary acquisition in 9-10 year old Finnish children learning English as a second language over a three year period. Children had to repeat aloud tape-recorded pseudo-words sounding like English. A possible explanation for her results is that the critical factor in pseudo-word repetition is trace quality in the phonological input store. Service concluded that the ability to represent unfamiliar phonological material on working memory underlies the acquisition of new vocabulary items in foreign language learning. Unfortunately Service did not distinguish between item and order components of phonological STM.

Cheung (1996) reported a similar association in 12 year old native Chinese (Cantonese) speaking children: Nonword span for items conforming to English phonology was used to measure phonological memory and was found to be generally predictive of the number of trials needed for acquiring certain English (L2) new words. However, the relationship was only found in those children whose English vocabulary size was below the group median suggesting a shift from dependency on phonological memory to dependency on long-term knowledge for vocabulary acquisition with increasing proficiency. Cheung argued that verbal STM plays a part in language learning because it interacts with extant knowledge of lexical forms in LTM. Like Service, Cheung did not investigate item and order components of verbal STM but rather used nonword span measures, which mixes both components within one task

Thorn and Gathercole (1999) investigated the relationship between verbal STM and language-specific knowledge in three language groups: English-French bilingual children, non-bilingual English children learning French (who were dominant in their first language), aged 6-9 years, and English monolingual children aged 4-8 years. They looked at the ability of STM performance (as measured by digit span and nonword repetition tasks) to predict language specific knowledge. First, monolingual English children, English-French bilingual children and English children learning French as a second language were compared on measures of phonological STM and vocabulary in both languages. Performance on tests of STM mirrored familiarity with English and French: Children with greater vocabulary knowledge in German could recall higher numbers of both words and nonwords in German while children with greater vocabulary knowledge in English could recall higher numbers of both words and nonwords in English. Thorn and Gathercole (1999) therefore suggested that successful learning of a second language depends on the integrity of phonological representations of the native language in long term ‘lexical’ memory. In the second part of their study, Thorn and Gathercole (1999) examined two groups of children with good knowledge of English and French: Native bilingual children and non-native bilingual children who had greater knowledge of their native than second language. Here, the results of the first study were replicated: Children who had acquired both languages simultaneously from birth and had comparable knowledge of English and French vocabulary scored equivalently on the English and French versions of two STM measures: digit span, and nonword repetition. The non-native bilingual children were better at repeating unfamiliar nonwords typical of the sound structure of their first than their second language. The authors conclude that phonological STM is not language-independent but rather functions in a highly language-specific way depending on the integrity of the phonological network in a specific language.

The relative contributions of phonological STM and LTM knowledge to vocabulary knowledge in a second language was investigated by Masoura and Gathercole (2005). Their participants were forty Greek children (aged 8 – 13) who were studying English at primary school. Results showed a) that the children’s speed of learning new English words in a paired-associated learning task was strongly influenced by their current English vocabulary knowledge and b) this was independent of phonological memory skills assessed by a pseudo-word repetition task. The latter finding did not appear to be attributable to other potentially confounding factors that distinguished the children, such as age, nonverbal ability and the period of studying English. This finding might appear to be in conflict with previous evidence that phonological STM makes a contribution to learning of the sound patterns of new words that is independent of vocabulary knowledge (see Gathercole, et al., 1997), however in the Gathercole et al. (1997) study 5-year old monolingual children attempted to learn nonwords selected to be of low English word-likeness which simulated the acquisition of new vocabulary in an unfamiliar language. In such a situation, stored phonological knowledge similar to the novel form is unlikely to be available to support the learner`s attempt to build an enduring representation of the new sound pattern and he/she has no choice but to rely on temporary phonological traces in STM. The authors argue that the processes involved in learning new words in a highly familiar second language may be very different. In their study in 2005, phonological memory scores were closely linked to English vocabulary knowledge (similar to the results found by Thorn & Gathercole, 1999). The authors suggest that in learners with considerable familiarity with a second language, new foreign vocabulary acquisition is mediated largely by the use of extant lexical representations whereas learners of a new language might need to rely mainly on their phonological skills.

Bilingual auditory memory span and the influence of articulation time was investigated by Chincotta and Underwood (1998). Thirty six 15 year old Finnish-Swedish school children took part in their study. Language dominancy (i.e. more dominant in Finnish or Swedish) was evaluated by a questionnaire. They found articulation rate for items with no pre-existing lexical representations (nonwords) could predict memory span better than words in either their dominant or non-dominant language. When looking at the results in more detail, memory span for words varied as a function of both articulation time and language dominance in unbalanced BLs, who were dominant in one language. In balanced BLs, who speak both languages equally well, an equivalent memory span between the languages was found. This indicates influential contributions from factors related to language fluency and the strength of lexico-semantic representations.

The studies of monolingual adults reviewed in Section 6, this chapter, have shown a strong association between lexical learning and STM capacity, especially STM for serial order information (see Section 6.1.). Studies of bilingual speakers suggest that while phonological STM capacity seems to be an important early predictor of second language learning, vocabulary knowledge becomes the main factor that drives lexical learning in learners with considerable familiarity in a second language (e.g. Cheung, 1996; Gathercole, et al., 2001; Masoura & Gathercole, 2005; Thorn & Gathercole, 1999). From the studies above it can also be concluded that phonological STM is not a language-independent system but rather functions in a highly language-specific way. While adding interesting insight into the role of STM in bilingualism, none of these studies differentiated between verbal item and order STM, despite the fact that recent studies with ML speakers suggest that the distinction of these two components may be critical for vocabulary learning (see this chapter, Section 4).

As research with bilingual populations involves so many practical and methodological issues, not many studies have yet investigated item and order STM in bilingual adults and children. Only one study with BL adults has so far investigated the relation of verbal item and order STM components on vocabulary learning in BL speakers: In 2008, Majerus, Poncelet, Van der Linden and Weekes examined 52 adult English-French bilingual speakers learning new words. A word-nonword paired-associate learning task was administered with nonwords obeying French (L2) phonotactic rules. Item STM was measured by a delayed single nonword recall task, the words of this task where constructed with English phonotactic rules. An auditory digit span task was used to investigate serial order STM. Serial order memory was the most important predictor of word-nonword learning, and no evidence was found for item short term memory as a predictor.

Studying BL participants can help to further clarify the question of the importance of item and order STM in vocabulary acquisition when two languages are involved. In addition, it can help to clarify the role of item and order STM in different language dominancy levels as BL speakers are only very rarely truly balanced bilinguals.

8. Neuropsychological and Imaging Data Supporting Item and Order Distinction in Verbal STM

8.1. Research in Neuropsychological Patients

Brain damaged patients have given important insights to the relationships of short term memory and word-learning abilities. In previous studies, phonological STM was often evaluated using nonword repetition tasks with increasing number of syllables (i.e. first nonwords with one syllable, then two syllables, three syllables and so on). However, this task can be interpreted as a mix of a serial order and item STM task, not separating these two STM components. For example, Baddeley, Papagno and Vallar (1988) report a patient, PV, who, after a left-hemisphere stroke showed a very pure deficit in short-term memory: She showed a selective impairment of auditory memory span and memory span for nonwords: When asked to repeat nonwords consisting of two to five syllables, presented in lists of length one to four, PV was only able to repeat single disyllabic items and a maximum of 2-3 monosyllabic words. Performance was slightly better when stimuli were presented visually but still impaired. While PV was able to learn pairs of meaningful words (here her scores were within the normal range, when compared to a group of matched controls), she was unable to learn to associate a familiar word with an unfamiliar item from another language, especially when the task was presented verbally. The authors concluded that STM phonological storage is important for learning unfamiliar verbal material (i.e. learning a new language). Trojano and Grossi (1995) report a patient, SC, who has selective auditory phonological coding deficits and also showed a defective auditory verbal STM. Yet, he was able to learn lists of words: His verbal and spatial span, measured by a list of digits and bisyllabic words, was quite low - SC was only able to remember 2-3 digits and words in a row. His visuo-spatial span on Corsi`s block tapping task was normal. In a verbal learning task, he had to learn a series of 10 bisyllabic high-frequency words and was able to learn them after 10 presentations, which is comparable to non-impaired population. In a paired associate word and nonword learning task, SC could learn all words in a list, but was unable to learn nonword lists. The authors supported Baddeley et al.`s (1988) conclusions that learning lists of known words can proceed through the activation of lexico-semantic units, notwithstanding the defect of phonological STM. However, in the learning of novel words, the maintenance of their STM forms is critical if long-term representations are to be created.

Interestingly, recent neuropsychological data have shown that in some patients' serial order and item STM capacities can be selectively impaired: In 2000, Knott, et al. investigated auditory verbal STM in an English speaking patient, FM, who presented with a progressive fluent anomic aphasia. They found normal auditory verbal STM as measured by digit span memory but significant impairment in immediate serial recall of short sequences of familiar words and delayed repetition tasks (i.e. reproducing a single word after a filled delay of a few seconds). FM produced numerous phonological errors in both tasks, compared to normal subjects, which often consisted of phonological segments from the intended target word concatenated with segments from other words in the stimulus sequence. Compared to normal subjects, FM`s errors were primarily phonological errors, rather than serial recall errors (i.e. words recalled in the wrong position), indicating that her major difficulty lay in maintaining the phonological integrity of the items she was attempting to recall, not their serial position. Importantly, these errors were not observed in her spontaneous speech, naming or immediate single word repetition and hence these errors did not arise from a simple phonological planning difficulty. The authors concluded that auditory verbal STM might be crucially supported by activation of the lexical phonological representations responsible for production of content words in speech.

Majerus, Norris and Patterson (2006) report two English speaking patients suffering from semantic dementia. Four experiments were conducted. The first investigated semantic knowledge and item and serial order recall using real words in an open list (i.e. none of the words appeared twice): High- and low imageability, monosyllabic words, matched on number of phonemes and frequency, were put in five-word lists. The lists were presented auditorily and patients had to complete 10 lists by repeating the sequences in correct serial position. Both patients showed an advantage for high imageability words (like the normal population control group). However, they showed an abnormal profile in the number of item and order errors produced. Significantly more item errors were made compared to controls, including phonological blends and types of nonword response. Second, serial order errors were very rare for the patients. Imageability, a semantic factor, influenced item STM more than order STM in the patients with semantic dementia, unlike in controls, where order memory is also affected by imageability. The authors suggested that this might be due to a gradual degradation process that could have a disproportionate impact on the sparser representations of abstract, low-imageability words. If that were true, a decline in item STM performance for both high- and low-imageability words would be predicted, while the normal advantage for high imageability words would be maintained. This is exactly what was observed in Majerus et al.`s (2006) first experiment.

In a second experiment, item and order recall for closed item sets were explored: This procedure maximizes the likelihood of order errors as the items are the same in the different trials, and only their serial position changes. The authors hypothesized that the results from their first experiment would be reinforced and extended, if the new procedure still yields a major discrepancy between the proportions of item and order errors relative to controls. In this experiment, the authors used 10 lists of five phonologically similar words (ram, map, cat, mat, ham) and 10 lists of five phonologically dissimilar words (soap, nail, leaf, duck, pen). Words were matched across lists for frequency and concreteness. In the control group and patients the advantage for phonologically dissimilar over similar lists was significant. However, patients' performance in terms of accuracy was below normal range. Both patients made significantly more item errors (blends and phonologically related or unrelated nonwords) for phonologically dissimilar but not for phonologically similar words. The proportion and number of order errors was similar to those in controls. The results support the dissociation of item and order information observed in experiment 1.

The third experiment looked at item retention capacities for phonological and lexico-semantic information using nonword lists. Here, the authors explored the influence of sublexical and lexico-semantic knowledge on STM for item information. They hypothesized that if poor verbal STM performance is related only to degraded lexico-semantic knowledge, normal recall performance for information that is not influenced by lexico-semantic knowledge should be expected. If on the other hand long term memory's phonological contribution to short term memory is sublexical, then the effects should be comparable to that observed in healthy participants. Lists of nonword stimuli were presented auditorily via headphones (like in the previous experiments). High and low phonotactic frequency CVC nonwords were used as stimuli. They were presented in four-item sequences and there were eight trials for each nonword condition and each item only occurred once during the task. Also, a delayed repetition of high and low phonotactic frequency nonwords was introduced. Here, each nonword was presented in isolation, followed by a 5-second delay during which the participant counted aloud backwards. Patients' performance was comparable to controls in both accuracy and types of errors.

In their last experiment, the authors investigated the learning of new serial order and item information. As discussed in Section 3 in this chapter, Baddeley and colleagues have established that a well-functioning verbal STM system is essential for learning new phonological form (see e.g., Baddeley, et al., 1998; Baddeley, et al., 1988). More recently, it was argued that it is specifically the serial order component that is critical for learning new phonological information (e.g., Burgess & Hitch, 1999; Cumming, Page, & Norris, 2003; Gupta, 2003; Gupta & MacWhinney, 1997). The authors argue that individuals with preserved memory for serial order might therefore be expected to also have a preserved ability to learn new phonological information. The aim of experiment 4 was to explore learning for new phonological information without any major contribution of semantic-level processing. Two lists of five VCV nonwords had to be learned, there were six learning trials for each condition. Both patients were impaired relative to controls on almost all measures, despite their preserved capacity to learn and retain serial order. Majerus et al. (2006) conclude that, taken together, these data support the view that capacities for recall of order information are most probably distinct from capacities underlying recall of item information.

In the same year Majerus, Glaser, Van der Linden and Eliez (2006) reported impaired performance on serial order short-term memory tasks but preserved item short term memory in 8 French speaking children with velocardiofacial syndrome (VCFS; a congenital, autosomal dominant condition that features cardiac malformations, cleft palate, a characteristic facial appearance and learning disabilities, in particular a severely delayed language development) compared to a vocabulary matched control group. The authors conclude that (at least some) patients with VCFS have important difficulties in storage of serial order information in verbal STM.

No patient study with bilingual participants exploring item and order STM has yet been conducted.

Taken together, the data of patients provide important support for the proposal that language knowledge is a major determining factor of verbal STM capacity and highlight the necessary distinction of processes involved in item and order recall. In addition they support the hypothesis that the serial order component is distinct from the item STM component in verbal STM.

8.2. Neuroimaging Data Supporting Item and Order Distinction in Verbal STM

8.2.1. Functional Magnetic Resonance Imaging

Functional magnetic resonance imaging (fMRI) is used to measure the change in blood flow (hemodynamic response) related to neural activity in the brain. Of interest in fMRI studies is the blood oxygen level-dependent (BOLD) signal which, relative to a baseline, may increase or decrease in specific brain regions, allowing inferences to be made concerning the role of those regions in cognitive tasks. The biggest advantage of fMRI over other neuroimaging techniques such as electroencephalography (EEG) is its high spatial resolution (between 1-3mm) and that it can record signals from all brain regions, unlike

EEG which can only directly measure electrical activity at the scalp. Source localization algorithms may identify sources of the activity in other parts of the brain, but they are problematic and there is nothing equivalent to looking at all the brain at once.

Functional neuroimaging studies have identified a number of brain regions that are differentially activated when participants perform memory for serial order and memory for item identity tasks, as well as other brain regions that are shared between the tasks. Henson, Burgess and Frith (2000) for example investigated recoding, storage, rehearsal and grouping in verbal short-term memory using fMRI with healthy adult volunteers. Their aim was to localise the processes involved in verbal short-term memory for sequences of visual stimuli (letters and symbols). They identified a network of left-lateralised areas, including posterior temporal regions, supramarginal gyri, Broca's area and dorsolateral premotorcortex, which was specifically involved in verbal STM for order information. Their findings were consistent with the suggestion that verbal item information is represented in left posterior temporal areas and short-term storage of phonological information in left supramarginal gyrus. The authors suggested that the left dorsolateral premotor cortex was involved in the maintenance of temporal order, possibly as the location of a timing signal used in the rhythmic organisation of rehearsal (see also Catalan, Honda, Weeks, Cohen, & Hallett, 1998; Halsband, Ito, Tanji, & Freund, 1993). Broca's area on the other hand supports the articulatory processes required for phonological recoding of visual stimuli.

Marshuetz, Smith, Jonides, DeGutis, and Chenevert (2000) investigated item and order information in working memory using fMRI. In each task, five letters were presented for storage, followed after a brief interval by a set of probe letters. In the item memory task, the two letters were identical and the subject had to indicate if the letter presented was one of the items they just saw. In the order memory task the letters were different and subjects had to indicate if the two letters were in the order in which they saw them before. They found that the parietal and prefrontal cortices were more activated in order STM conditions when compared to item STM condition. As parietal activations overlapped those involved in number processing the authors suggested that the underlying representation of order and numbers may share a common process coding for magnitude as order information is numerical.

The majority of work that has explicitly compared item and order activation using fMRI comes from Majerus´ group in Belgium. Majerus, et al. (2005) showed that the posterior superior temporal gyrus was activated during tasks that require the temporary storage of unfamiliar phonological information, such as single nonwords. Majerus, Poncelet, Van der Linden, et al. (2006) used fMRI to directly compare cortical activation during both item and order STM tasks. In both the item and order task participants had to read four words, matched for linguistic features such as number of letters, frequency etc., and remember them in their correct order. After the four words two words were presented and the participants had to judge if they had occurred in that order before or not. In the item STM condition, four words appeared and the participants were asked to remember the item identity of the words. When two words were presented at recognition, participants were asked if both of them had occurred in the list before or not. The authors found that the order working memory task yielded greater activation in the right intraparietal sulcus, right cerebellum and bilateral premotor cortex as compared to the item STM task. The item condition, compared to the order condition, resulted in more activity in the superior temporal gyrus (superior temporal sulcus) and the left fusiform gyrus. These regions are associated with phonological and orthographic processing respectively (Binder, et al., 2000; Bolger, Perfetti, & Schneider, 2005; Scott, Blank, Rosen, & Wise, 2000).

Another study by Majerus, et al. (2007) explored the validity of an attentional account for the involvement of the left intraparietal sulcus (IPS) in visual STM tasks. This attentional account was inspired by Cowan (Cowan, 1995, 1999; Cowan, et al., 2005), whose cognitive framework of short-term storage proposes that STM is the result of temporary activation of long-term memory representations which are held in the focus of attention. In the Majerus, et al. (2007) study, 21 right handed native French speaking participants were presented with four faces ordered horizontally followed by a maintenance phase indicated by a fixation cross. The retrieval phase consisted of an array of two probe faces and participants had to indicate if item or spatial order information for the two probe faces was the same or not. In the order condition, participants had to judge whether the probe face presented on the top of the screen had occurred in a more leftward position than the probe face presented on the bottom of the screen. In the item condition the probe faces were two copies of the same face and the participants had to judge whether the probe faces were identical to one of the faces in the memory list. The authors hypothesized that if the left IPS acts as an attentional modulator, it should be active in both item and order STM conditions but should be associated with activity in different neural networks specialized in serial order or face identity processing. The IPS was indeed active during both conditions but during order encoding, compared to item encoding, the left IPS showed functional connectivity with order processing areas in the right IPS, bilateral premotor and cerebellar cortices, reproducing earlier results obtained in a verbal STM experiment (see Majerus, Poncelet, Van der Linden, et al., 2006). During item encoding, however, the left IPS showed preferential functional connectivity with right temporal, inferior parietal and medial frontal areas which have been shown to be involved in detailed face processing (Haxby, Hoffman, & Gobbini, 2000; Henson, Hartley, et al., 2003; Kanwisher, McDermott, & Chun, 1997; Platek, et al., 2006; Sugiura, et al., 2000). The authors concluded that the left IPS seems to serve an attentional function in visual STM but might be important also as attentional modulator in a variety of STM tasks.

Majerus, Bastin, et al. (2007) have attempted to outline the neuroanatomical basis for such an account and point out that depending on the type of information that has to be processed (for example, item vs. order, verbal vs. visuo-spatial), different representational and processing systems will be recruited, activating different neural substrates. Yet, in order to keep information available to consciousness across the different stages of a STM task (i.e. encoding phase, maintenance phase and retrieval phase), the activity within these different neural substrates has to be maintained and synchronized via focused attentional processes which have been proposed to be implemented in the left IPS (see also Majerus, Poncelet, Van der Linden, et al., 2006; Ravizza, Delgado, Chein, Becker, & Fiez, 2004).

In 2009, Majerus, D'Argembeau, et al. investigated the commonality of neural networks for verbal and visual short term memory. On the basis of their previous results, they hypothesised that neural networks involved in attentional processing are engaged during memory for both serial order and item identity but that there are also independent neural networks involved in serial order processing underlying STM. Moreover, these networks were assumed to be independent of modality, i.e. active for both verbal and visual stimuli. Participants had to remember sequences of nonwords and unfamiliar faces in an item and order STM paradigm. The tasks were similar to those used in previous studies (visual study with unfamiliar faces: Majerus, et al., 2007; verbal study with words: Majerus, Poncelet, Van der Linden, et al., 2006). In the nonword task, the correct order or item identity of four nonwords had to be remembered. Participants had to indicate if item or order information for the two probe stimuli matched information in the memory list or not. The visual task was similar only exchanging nonwords for unfamiliar faces. For encoding and retrieval phases on the order memory task, they found activity in an identical fronto-parieto-cerebellar network comprising the left IPS, bilateral dorsolateral prefrontal cortex, and the bilateral cerebellum. In contrast, cortical activity during the serial order STM tasks was found to be centred around the right IPS in both verbal and visual modality tasks. They concluded that memory for serial order emerges from the development of independent attentional and serial ordering processes.

Not many neuroimaging studies have investigated cognitive processes in BL people. Such studies could help to further explore underlying neural mechanisms for item and order STM in relation to vocabulary knowledge, and how the effects of speaking more than one language may interact with these processes. When comparing high and low proficient BL speakers, the influence of proficiency on item and order STM can be explored (for more details see discussion in Section 7 in this chapter). By comparing BLs who have acquired a language from birth with BLs who have acquired a language only at later years, the effect of age of acquisition on item and order STM in relation to language acquisition can be investigated. These insights can also be used to further develop models of language processing and broaden the understanding of which tasks are important for acquiring a (first and second) language.

One of the few studies that have used neuroimaging on BL participants was carried out by Majerus, Belayachi, de Smedt, Leclercq, Martinez, Weekes and Maquet (2008). They investigated whether the neural substrates of order STM can serve as markers for bilingual language proficiency and examined the processing of item and order in high and low proficiency French-German speaking bilinguals residing in Eastern Belgium. They found that activation in only the neural networks supporting order short-term memory could differentiate the two groups - during order STM tasks but not item STM tasks, the high proficiency group showed increased activation in the lateral orbito-frontal and the superior frontal gyri. This activation was assumed to reflect the updating and grouped rehearsal of serial order information based on similar findings using fMRI with adult monolingual speakers (see Majerus, Poncelet, Van der Linden, et al., 2006). A functional network for order memory involving left IPS, right IPS and right superior cerebellum was found in the high proficiency group, whereas the low proficiency group showed enhanced activation in the left IPS and bilateral superior temporal and temporo-parietal areas, regions known to be activated during item STM processing in monolinguals (see Majerus, Poncelet, Van der Linden, et al., 2006). The authors suggest that low proficiency bilinguals activate STM networks for order in a less efficient manner than high proficient bilinguals. This relatively strong claim predicts that storage and learning capacity for the order of verbal sequences depends on the left IPS for all participants but may also recruit the right IPS for highly proficient bilingual speakers.

In summary, the results from a number of functional neuroimaging studies support the behavioural studies and patient data and support a distinction between item and order STM. The neuroimaging studies seem to suggest that item STM in adults activates a left fronto-parieto-cerebellar network, whereas order STM tasks engage a right parieto-temporal network. In addition, differences in item and order STM processing were found in high and low BL speakers, indicating at least some language-specific differences within the two verbal STM components.

One limitation of MRI studies is that they reveal little about the time course of processes used in verbal STM tasks. This limits the conclusions that can be drawn about dissociations between memory for serial order and item identity observed in imaging studies. For example, similar regions of the brain may be active on two memory tasks which might allow the conclusion that putative STM memory components actually reflect common processes including focussed attention and executive control (Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006). However, analysis of the time course of processing on each memory task could show a temporally distinct pattern.

The above studies give an overview of neuropsychological evidence for item and order verbal STM. However, so far only studies with patients and neuroimaging studies using fMRI have been conducted. Other cognitive neuroscience techniques have not yet been used to investigate differences in item and order verbal STM. In this thesis two other forms of cognitive neuroscience tools are used to investigate item and order verbal STM. One is Transcranial Magnetic Stimulation (TMS) and the other Electroencephalography (EEG). TMS is an especially useful tool that can be used to explore the importance of regions of interest in the brain by artificially disrupting neurons in those regions in healthy participants and then investigating the subsequent impact of such disruptions on behavioural data (i.e. reaction times and accuracy). EEG on the other hand measures electrical activity on the scalp with high temporal resolution, and can detect changes in amplitude between item and order STM tasks in measures of milliseconds. Below is a brief review of these two techniques.

8.2.2. Transcranial Magnetic Stimulation

In recent years psychologists have begun to explore brain-behaviour relationships with transcranial magnetic stimulation (TMS). TMS can precisely link explicit function to a focused cortical area. It is used to disrupt the elementary unit of the nervous system; neurons in the brain. A magnetic coil is held close to the head in a constant position. Magnetic pulses temporarily disrupt neural processing in the stimulated cortical area of interest which can then affect performance on a behavioural task (e.g. reaction times are slowed down or accuracy is less precise). Hence, TMS is a powerful tool for psychologists and cognitive neuroscientists who are interested in investigating the relationship between cortical activity and cognitive processes. For more details on TMS please refer to Section 2 in Chapter 3, strengths and weaknesses of TMS techniques can be found in Appendix B2. So far, no one has used TMS to explore differences in item and order STM in healthy participants. Data reported in this thesis are the first to use this technique (see Chapter 3).

8.2.3. Electroencephalography

Electroencephalography (EEG) is a non-invasive method of measuring brain activity through the skull and scalp during cognitive processing. It is a technique that is used for measuring where on the surface activity occurs and how quickly neurological reactions take place. The EEG in its raw form reflects thousands of simultaneously ongoing brain processes and hence is a very coarse measure of brain activity (Luck, 2005, p. 4). The brain response to a single stimulus or event of interest is not usually visible in the EEG recording of a single trial. In order to see the brain response to a given stimulus many trials must be conducted and the results must be averaged together, causing random brain activity to be averaged out. The outcome of this procedure is called event-related potential (ERP). ERPs can be used to investigate cognitive processing in relation to a given stimulus (Picton, et al., 2000). The greatest advantage of EEG techniques over fMRI is temporal resolution. It can detect changes within milliseconds, while other methods such as fMRI or PET only have time resolutions between seconds and minutes. More details on strengths and weaknesses of EEG techniques can be found in the Appendix A7. No study has yet examined whether cognitive processes used in memory for serial order and item STM tasks also show distinct patterns in EEG. In addition EEG, as a non-invasive technique, allows us to test on children as well as adults, so we can test hypotheses about developmental influences on the neural mechanisms supporting item and order STM. Data reported in this thesis are the first to use this technique on children and adults to investigate further differences between item and order STM (see Chapter 2).

9. Conclusion

In conclusion, a substantial body of evidence suggests that the ability to store phonological information in short term memory is a key factor in early vocabulary acquisition, whereas extant vocabulary knowledge becomes the main factor that drives lexical learning in learners with considerable familiarity in a second language. It is also clear from the studies above (see Section 4, this chapter) that phonological STM is not a language-independent system but rather functions in a highly language-specific way.

In addition, recent findings suggest that the short term storage of “item” and “order” information can, to some extent at least, be dissociated. In monolingual and bilingual children and adults as well as in neuropsychological data of monolingual patients, it appears that STM processes that allow the serial order of phonological information to be reconstructed are particularly important for the learning of new phonological sequences in vocabulary learning. Recent theoretical accounts of short term memory also suggest a relationship between serial order STM capacity and new word learning (Botvinick & Plaut, 2006; Brown, et al., 1999; Gupta, 2003).

The aim of this thesis is to investigate item and order STM processes in monolingual and bilingual children and adults. First, electroencephalography (EEG) is used to investigate differences in the neural correlates of item and order processing in these populations. Then, TMS is used to test the hypothesis suggested by recent fMRI results that the left intra parietal sulcus (IPS) is involved in both item and order STM while the right IPS is only involved in order STM processes. A longitudinal developmental study with mono- and bilingual children investigates influences of item and order STM on vocabulary development. This study also tests the hypothesis that bilingual speaking children have better memory for serial order than monolingual speaking children. To foreshadow the results, bilingual speaking children do have better memory for serial order than monolingual children suggesting a direct relationship between second language acquisition and development of phonological STM. Finally, a behavioural study with monolingual adults investigates different item and order STM tasks and their influences on new vocabulary learning. In addition this final study uses correlational analysis to investigate the possible interdependence of different item and order STM tasks used in this thesis.

Chapter 2: Neuro-Electrical Correlates of Item and Order STM in Mono- and Bilingual Adults and Monolingual Children

1. Introduction

As described in Chapter 1 (see Sections 2, 4, 6.1 and 7), a large number of studies have shown that verbal short-term memory (STM) is strongly related to vocabulary knowledge (see e.g., Gathercole, et al., 1999; Gathercole, et al., 1992; Gupta, 2003). Recent research suggests that STM for serial order and STM for item information can be differentiated (e.g., Baddeley, et al., 1988; Henson, Hartley, et al., 2003; Knott, et al., 2000; Majerus, Norris, et al., 2006; Poirier & Saint-Aubin, 1996; Trojano & Grossi, 1995). In addition, current models of verbal STM provide theoretical accounts of separate item and order STM components (Botvinick & Plaut, 2006; Burgess & Hitch, 1999; Henson, 2001) and more specifically their involvement in vocabulary acquisition (Brown, et al., 1999; Gupta, 2003; Majerus, 2008). However, research on this topic is still in its infancy, and so far only very few neuroimaging studies have investigated the extent to which item and order STM are mediated by different neural mechanisms.

Recent functional neuroimaging studies have highlighted a number of brain areas activated by both item and order STM components and some that are apparently unique to each of these components (for more details see Section 8.2 of Chapter 1). It has been suggested that in ML adults, item STM involves a left fronto-parieto cerebellar network, whereas order STM tasks engage a right parieto-temporal network (Majerus, et al., 2007; Majerus, D'Argembeau, et al., 2009; Marshuetz, et al., 2000). As discussed in Section 8.2 in Chapter 1, differences in activation and connectivity patterns between item and order processing have also been found in BL adults. Majerus et al., (2008) identified a functional network for order memory involving left IPS, right IPS and right superior cerebellum in a high proficiency group, whereas the low proficiency group showed enhanced connectivity in areas involved in item processing namely the left IPS and bilateral superior temporal and temporo-parietal areas. Behavioural research suggests that item and order processes have different developmental trajectories in children (Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006). However, no neuroimaging data are available for children.

Data from brain imaging reveal information about the spatial parameters (i.e. where in the brain activation takes place) whilst people perform verbal STM tasks. However, fMRI studies reveal little about the time course of processes used in verbal STM tasks. For example, similar regions of the brain may be active in two memory tasks, but the level of activation may peak at different time points. An analysis of the time course of processing on each memory task could show a temporally distinct albeit spatially overlapping pattern. Such a finding would provide further evidence in support of the suggestion that serial order and item identity are dissociable processes.

EEG is the recording of electrical activity along the scalp. It has very fine temporal resolution (Friedman & Johnson, 2000). Unlike PET and fMRI techniques, precise quantification of the characteristics of neural activity in the brain can be observed using this method (Friedman & Johnson, 2000). Event related potentials (ERPs) can elucidate stages of processing and can hence help to pinpoint differences in item and order STM processing, i.e. if differences occur in an earlier or later stage of stimuli presentation.

This chapter comprises three studies with the aim of revealing possible different neural mechanisms underlying item and order STM in three groups of participants: Monolingual English speaking adults, English/German bilingual adults and monolingual English speaking children. Monolingual adults as the first group were chosen in order to determine whether item and order STM have different neural signatures in a healthy group of adults who only speak one language. Bilingual participants were then included as a second group for two reasons: (1) to determine whether item and order STM have different neural signatures in BL speakers (as found in recent fMRI studies, for details see Section 8.2. in Chapter 1) and (2) to investigate how the neural signatures of item and order STM processing differ between monolingual and bilingual adults, who have a richer vocabulary pool than monolinguals. Monolingual children were investigated as third group, to find out if (1) item and order STM also show distinct neural signatures in a developmental sample as suggested in behavioural experiments (for a review see Section 6.1. in Chapter 1) and (2) to compare the neural signatures of item and order STM in children, who have a much smaller vocabulary pool than adults, to the underlying neural processes of item and order STM in ML adults, in order to compare item and order STM processing across ages.

The key prediction is that for all three groups there will be a difference in the EEG signals associated with order STM compared to item STM. This prediction is based on behavioural results that show that performance on item and order STM tests can be differentiated within these three groups (for a review see Sections 6, 7 and 8 in Chapter 1 for a review).

As discussed in Section 6.1. of Chapter 1, it has been suggested that order STM is an especially critical determinant of language learning capacity (Jefferies, et al., 2006; Leclercq & Majerus, 2010; Majerus, Belayachi, et al., 2008; Majerus, Heiligenstein, et al., 2009; Majerus, Poncelet, Elsen, et al., 2006). If order STM is related to language learning, it is possible that BL speakers will process order STM differently to ML speakers as they have acquired two languages as opposed to monolingual speakers who only acquired one. This argument is strengthened by recent behavioural studies: Papagno and Vallar (1995) compared polyglots (participants who are fluent in three or more languages) to non-polyglots and found that polyglots had a superior level of performance in verbal STM tasks (auditory digit span and nonword repetition) as well as in a paired associate learning test. The authors argued that their results suggest a close relationship between the capacity of phonological memory (based on the WM model) and the acquisition of foreign languages. Also Gupta (2003) suggested that the high correlations between serial recall, nonword repetition and word learning in polyglots could be due to polyglots' ability to speak multiple languages, and this might have an effect on performance in serial recall or vice versa.

Item identity information refers to phonological, orthographic and/or semantic properties that define the verbal stimuli being held in STM (see

Chapter 1, Section 1). The inclusion criterion for BL speakers was English language knowledge comparable to ML English speakers as measured with active and passive vocabulary tasks (see Section 6.1., this chapter for further information). Hence only highly proficient English/German BL adults were permitted to take part in this study. As all BL speakers showed comparable vocabulary knowledge to ML participants, item STM is expected to be similar in both groups.

Research also suggests that item and order STM show different developmental trajectories in monolingual children (see Section 6.1. in Chapter 1 for a review). By comparing the neural processing of item and order STM in ML children and ML adults the aim is to track down developmental changes in the event-related EEG signal. This will help to provide further evidence of how item and order STM might be related to vocabulary acquisition, i.e. if item STM reflects knowledge of phonological orthographic and semantic properties, age-related differences in EEG signals would be expected. On the other hand EEG signals related to order STM, if more related to learning a (second) language, should be similar in ML children and adults as both only learn one language (namely English).

Taken together, these studies aim to achieve a clearer understanding of neural substrates involved during item and order STM processing and their relation to interindividual differences in language learning capacity and across different ages.

2. Electroencephalography

Electroencephalography (EEG) provides a direct measure of real time brain activity at the millisecond level even without the need of an additional task from the participant other than e.g. reading for comprehension (Moreno, Rodríguez-Fornells, & Laine, 2008). It measures voltage fluctuations on the scalp, which result from current flows in cortical neurons (see Figure 6 for a picture of EEG-recording on a child). The EEG in its raw form is a coarse measure of brain activity and is not able to measure specific neural processes (Luck, 2005). However, specific EEG responses can be linked to events that require cognitive processing. These are called event related potentials (ERP) as they always appear in combination with a specific event. ERPs reveal changes in cognitive processing during task performance (Picton, et al., 2000). ERPs can be recorded from the human scalp and extracted from the ongoing electroencephalogram (EEG) using filtering and signal averaging methods (Picton, et al., 2000).

Figure 6: EEG for a child

The magnitude of the voltage changes associated with ERPs is very small in comparison to the ongoing changes in the amplitude of the EEG, which constitutes the noise from which the ERP signal has to be extracted. At least 20 to 50 trials belonging to the same experimental condition are needed for each participant, and these are then averaged together, to obtain ERP waveforms with satisfactory signal-to-noise ratio. The average waveforms represent estimates of time-locked neural activity, typically elicited by the presentation of stimuli belonging to different experimental conditions (Rugg & Allan, 2000).

The greatest advantage of ERP techniques over fMRI studies is temporal resolution. EEG recording can detect changes in brain activity within milliseconds. ERPs can therefore accurately measure when processing occurs in the human brain (Picton, et al., 2000). This high temporal resolution allows upper-bound estimates of the time required by the nervous system to discriminate between different classes of stimuli (Rugg & Allan, 2000). ERPs provide a window into the online processing that occurs between a stimulus presentation and any behavioural response it elicits. Critically, the activity of interest can be observed well before a behavioural response is produced. This makes it possible to determine which temporal stages of processing are affected by a specific experimental manipulation independent of any peripheral task demands. EEG is therefore an appropriate technique with which to examine differences in the neural mechanisms underlying the processing of item identity and serial order during encoding and retrieval phases. ERPs can be measured across different experimental conditions.

ERPs can be used to investigate whether functionally dissociable cognitive processes are engaged in different experimental conditions (Rugg & Allan, 2000). However, this logic depends on the assumption that there are grounds for proposing that each condition engages at least partially non-overlapping neural and hence functional processes. In terms of the present study, if two experimental conditions using the same stimuli such as memory for serial order and memory for item identity are associated with qualitatively different patterns of scalp electrical activity, then it can be assumed that they reflect dissociable cognitive processes.

Importantly, strong relationships between selected ERP components and memory processes involving learning and recalling or recognizing simple verbal stimuli, such as words, have already been established (B. R. Dunn, Dunn, Languis, & Andrews, 1998; Fabiani, Karis, & Donchin, 1985, 1986, 1990; Garrett-Peters, Dunn, Dunn, & Andrasik, 1994; Karis, Fabiani, & Donchin, 1984; Paller & Kutas, 1992; Paller, Kutas, & McIsaac, 1995; Rugg & Nagy, 1989; Sanquist, Rohrbaugh, Syndulko, & Lindsley, 1980; Van Petten & Senkfor, 1996).

The most important epochs and regions of interest will be explained and outlined in the following section.

2.1. Short Explanation of Mean Amplitude in EEG Analysis

Mean amplitude is the average voltage in microvolts (μV) of an ERP trace in a chosen time window under a specific peak. When analysing amplitude, the average voltage in a certain time window is compared across conditions (e.g. is the amplitude for P200 greater for item or order tasks?) or participants (e.g. is the amplitude for P300 greater in monolingual or bilingual speakers?). Refer to Figure 7 for a graphic depiction of mean amplitude in EEG analysis.

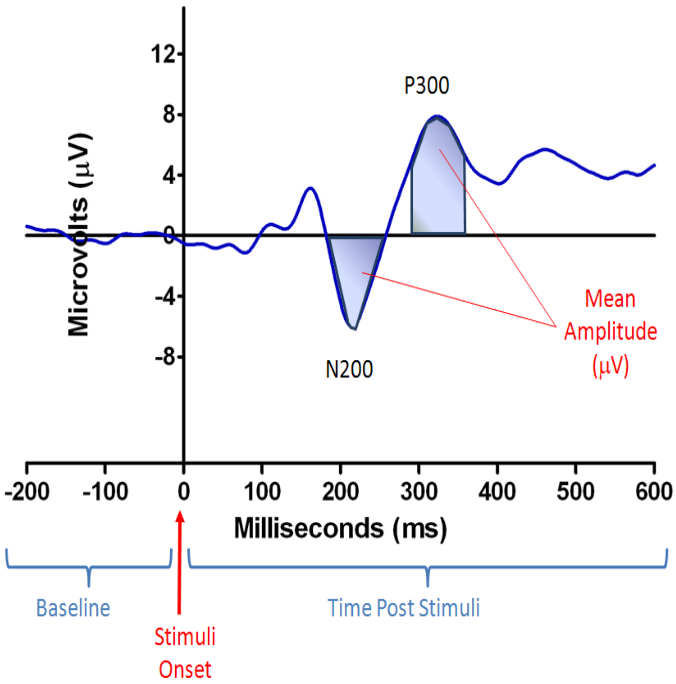

Figure 7: Explanation of mean amplitude in the EEG analysis

3. ERP Studies of Verbal STM

A large amount of research has used EEG to investigate STM processes. Several STM-related changes in ERP components have been identified. The most common are the P200, P300, and the Late Positive Component, LPC. The following sections describe key studies that have measured these components whilst participants performed tasks that seem to primarily involve either item STM tasks (such as old/new recognition judgments) or order STM tasks (such as memorizing lists of items and recalling from them in the correct position) or a mix of both (such as recalling nonwords, where the phonemes (items) and the position of the phonemes (order) have to be kept in memory)[5]. It needs to be pointed out that all these different experimental tasks have so far been used to investigate STM in general, but no study has yet separated the two components item and order STM. In fact, most studies used tasks that combined item information and serial order information (also reflected in earlier behavioural studies, for more details see Section 4, Chapter 1).

The following review aims to unveil STM components that might reflect item or order STM distinctly but as this will be very difficult a second aim is to understand the most common STM components further.

The P2 or P200 is a positive peak 150-275ms post stimuli that is often found around anterior (i.e. frontal) electrodes. It has been found to be related to endogenous or cognitive processing variables (McDonough, Warren, & Don, 1992), for example it is said to be an indicator of mapping from orthography to phonology (e.g., Meng, Tian, Jian, & Zhou, 2007) and some authors suggest that it may index mechanisms of selective attention (e.g., Hackley, Woldorff, & Hillyard, 1990), feature detection processes (Luck & Hillyard, 1994) and other early sensory stages of item encoding. Several researchers have shown the P200 component to relate positively to retrieval in short-term memory experiments (Chapman, McCrary, & Chapman, 1981; Friedman, Vaughan, &

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[5] One could argue that order STM tasks also always activate item STM and hence might also be seen as "mixed" tasks (see Section 4, Chapter 1 for a discussion on this matter).

Erlenmeyer-Kimling, 1981; Taylor, Smith, & Iron, 1990). Other researchers argue that the P200 amplitude is related to partial retrieval of semantic information from long-term memory into working memory (e.g., Barnea & Breznitz, 1998; Wlotko & Federmeier, 2007) as it appears to be related to subsequent recognition (Smith, 1993) or recall in short-term memory.

In a study by Adam and Collins (1978) participants had to remember lists of digits which were between 1 and 11 digits long. The digit lists were then followed by a test-digit. They had to judge whether or not the test-item had occurred in the list or not (also known as Sternberg-Paradigm; Sternberg, 1966, this task might reflect item STM as no positions of items need to be kept in memory). The authors report a positive-going evoked potential about 250ms post-stimuli reliably in all records for set sizes longer than three items. They suggest that P2 might reflect search processes (e.g. memory recall) as increasing digit lists markedly changed the ERP waveforms. In a study by Gevins et al. (1996) participants completed a STM task where they had to match each stimulus with a preceding stimulus occurring three positions before the match stimulus on either verbal or spatial attributes. In the control task, participants only had to press a button if an item occurred in the same position (spatial task) or was the same letter (verbal task), but not remember the last three items. They found that all stimuli elicited a P200 potential in the central region of the head. A significant effect of memory load was obtained with the P200 being enhanced in the STM tasks relative to the control tasks. Considering the task, this could possibly reflect order memory processes, as the position of each stimulus needed to be remembered.

P3 or P300, a positive peak around 300ms post stimuli appearing at parietal electrodes, is a well established ERP component which several authors suggest reflects neural mechanisms involved in context updating in working memory (Blumhardt, 1996; Donchin, 1981; Fabiani, et al., 1986; L. Howard & Polich, 1985; Key, Dove, & Maguire, 2004; Nittono, Nageishi, Nakajima, & Ullsperger, 1999; Pelosi, 1998; Pelosi, et al., 1992; Polich, 2007; Starr & Barrett, 1987). For example, Wiswede, Rüsseler and Münte (2007) found that differences in the amplitude of the P300 component are associated with updating of events in working-memory, stimulus significance, confidence in decision-making, decision-making processes, task difficulty, attention and the presence of a secondary task. On the other hand, Otten and Donchin (2000) point out that the relationship between P300 amplitude and subsequent recall depends on the *type of distinctiveness* attribute (i.e. change in the immediate surroundings of a stimulus) and memory strategies. Therefore it should not be ascribed to a generalized effect of distinctiveness on memory encoding processes. An explanation for these contradictory findings might be provided by Polich (2007). In a review paper he describes two P3-components: P3a, which he argues originates from stimulus-driven frontal attention mechanisms during task processing and P3b which originates from temporal-parietal activity associated with attention and seems to be related to subsequent memory processes, more specifically with memory recall performance.

In a study by Nittono et al. (1999), the authors investigated ERPs of individual differences in short term memory performance. Participants had to perform two and five-choice reaction time (RT) tasks. In the two-choice RT task (2CRT) two digits were presented and in the five-choice RT task (5CRT) five. Participants were required to press a button corresponding to each digit with a different finger. Reading span was also investigated as a measure of working memory. Participants with high reading span produced larger P300s than did persons with low reading span in the 5CRT task, but the difference was not significant in the 2CRT task. The authors suggest that individual differences in working memory capacity would affect initial stages of information processing as early as 300 ms after stimulus onset. Nittono et al. (1999) point out that the P300 increased as task demands increased as long as performance remained high. Dunn et al. (1998) invested the relation of ERP components to complex memory processing using a “rote” serial-order and an “elaborative” category memory task. In the serial order task, participants had to remember lists of words in the given order and then were asked to write the words down in order of presentation. In the categorical task, participants also learned word lists, which contained two inherent categories containing eight words each. Participants were instructed to discover and encode the words into the categories with a free recall phase. They found that a late P300 occurred particularly in the serial order task in frontal areas.

The late positive component (LPC) is a positive wave form that appears 500-800ms post stimuli over the frontal cortex, prefrontal cortex or in parietal areas. It is often seen when participants perform memory tasks and its amplitude has been found to be positively related to recognition and recall performance (Key, et al., 2004). Some researchers have argued that the LPC might be a form of late P300 (Fabiani, et al., 1986; Karis, et al., 1984; Polich, 2007) but this is a controversial position. Dunn et al. (1998) and other researchers (e.g., Paller & Kutas, 1992; Smith, 1993) argue that LPC is a separate component which may index several different processes such as feature encoding (in the frontal cortex, particularly the prefrontal cortex) and reconstructive or recollective processes (parietal LPC). Thus, as Dunn et al. (1998) point out, depending on the task during which the LPC is elicited (i.e. acquisition vs. retrieval) the LPC could index both relatively simple lexical or semantic encoding or more elaborative processes based on information stored in long-term memory (see also Besson, Kutas, & Van Petten, 1992; Paller & Kutas, 1992; Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991; Van Petten & Senkfor, 1996). Wolk et al. (2009) investigated ERP correlates of recognition memory with participants performing a word recognition memory task. Participants saw a list of words and then had to judge whether a word in the test list had been in the list before or not. They found increased LPC amplitude associated with recollection. In 1992, Pelosi et al. investigated wave form variations in auditory event-related potentials evoked by a memory-scanning task and their relationship with tests of intellectual function. They used a digit probe identification task with 1, 3 or 5 aurally presented digits followed by a single probe digit. Participants had to indicate whether the probe was present in the preceding memory set or not (Sternberg paradigm – reflecting item STM). The major intra-subject difference in the response wave form was the presence or absence of the late parietal positive wave (the authors call it P560). This wave occurred significantly more often in responses associated with larger memory sets and slow reaction times (RT), suggesting that its presence reflects subjective difficulty in performing a task.

Taken together recent ERP findings have shown that P200, P300 and LPC are all modulated by various STM processes However, the studies described in the above literature do not in general make a distinction between STM for item information or STM for order information (for a discussion of how “pure” tasks that assess these processes can be, please refer back to Section 4 in Chapter 1). None of the ERP components could be identified as relevant for only “item STM” or only “order STM” tasks. To detect a difference between the two types of memory one must design novel tasks (one maximising item STM and the other one maximising order STM) to find the possible subtle differences between the two processes. Hence, taking into account recent literature of STM (see Table 1 for an overview), the studies described in this chapter will use newly designed tasks to investigate possible differences in the neural substrate of the two STM components: item and order STM processing.

Name	**Polarity**	**Location**	**Indication**
P200	Positive peak 200 ms post stimuli	Frontal	Retrieval Short-term memory “storage” component
P300	Positive peak 300 ms post stimuli	Parietal	Context updating in working memory Memory recall performance
LPC	Positive Waveform 500-700 ms post stimuli	Frontal cortex	Feature encoding
		Parietal	Reconstructive or recollective processes

Table 1: Overview of important ERP memory components

4. Methods

4.1. EEG Data Collection

An EEG Geodesic Sensor Net (Electrical Geodesics, Inc.; EGI system) with 128 channels was used to collect data and the program NetStation to analyse data output. The analog-to-digital (A/D) rate was 1000 Hz. Individual electrodes were adjusted until impedance was below 50 $K\Omega$.

A bandpass filter of 1-30 Hz was applied, artefact detection was ± 150µV. The online reference was the centre point (channel CPz)[6].

4.1.1. Acquisition Procedure

The procedure was similar for all participants: Upon the arrival of the participant, he/she was shown the Geodesic net. Next, the participants' head circumference was measured and the appropriate net was chosen. The net then was soaked in the prepared electrolyte solution and the participant (or, in the case of the child participants their parents) was asked to fill in questionnaires and a consent form and to do the practice version of the experiment. It was explained to the participant that any movement during the EEG recording can cause artefacts in EEG (e.g. when they blink or move their eyes or head). After washing their hair thoroughly, the EEG-net was placed on the participant's head. Finally, the participant was led to the Faraday cage where the net was attached

[6] The reference point is generally at the centre (i.e. channel CPZ). However, if one of the target areas of interest is near this point, CPZ may pick up important information or it may reduce the size of the frequency as the frequency of CPZ is subtracted from the other channels. Therefore by selecting for example the mastoid electrodes (M1 and M2; these areas are mostly bone; the frequency they pick up is generally just noise) or to use a whole-head average as reference can be a solution against losing important information about voltage changes in single electrodes.

to the amplifier (Net Amps 200) and all electrodes were put in their correct position, i.e. standing upright in the right places.

The set up of the participant was then complete. Before running the experiment, the impedance level was measured to assure good recording. Using a pipette and electrolyte, all electrodes that did not conduct electricity properly (as seen on the computer) were moistened with electrolyte. When more than 2/3 of the electrodes were conducting well (working below the threshold settings), the experiment was ready to be run. The program NetStation 4.1. (Electrical Geodesics, Inc.) was used for data acquisition and analysis.

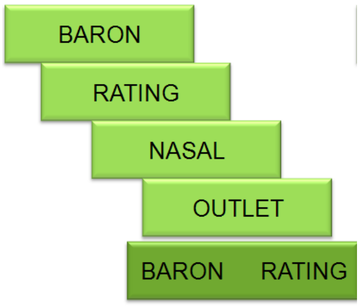
4.2. Materials

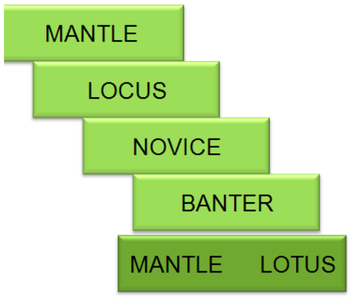
4.2.1. Task Description

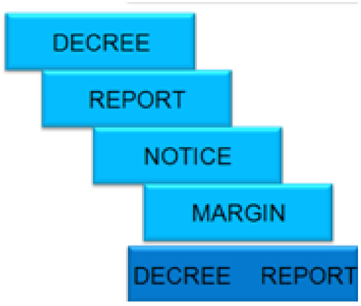
Participants were asked to perform two memory tasks: One task for item STM and a second task for order STM. Both tasks consisted of the sequential presentation of four words in a study phase followed by a blank screen and two probe words (see Figure 8 for details on stimulus duration and timing).

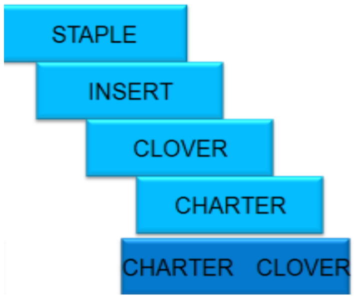
In the order STM task, the probe trials always contained two words that were adjacent in the study phase, but they were presented either in the same or the reversed order in the test phase. By probing adjacent but not distant positions, we were able to maximize the difficulty and sensitivity of the order STM condition as very precise order representations are needed when probing two adjacent items (for more details see Majerus, Poncelet, Van der Linden, et al., 2006). The task was to decide if the words had been presented in the same order or not (half were presented in the same order and half were not). Participants had to judge whether the probe word presented on the left of the screen had occurred before the probe word presented on the right.

In the item identity STM task either both probe words had been presented in the study phase or one had not been presented in the study phase but instead a word that differed in only one sound from the original word in the study phase (e.g.. manure instead of mature) was shown. The use of negative probes (i.e. the presentation of one member of the minimal pair in the study list and the other member in the probe array) was designed to increase the difficulty of the item STM condition because words differed only minimally from the target word. Participants had to judge whether the two probe words were identical to any of the words in the study list. For an overview of the two tasks including correct and incorrect examples see Table 2 and for more details on the specific stimuli used see Appendix A4.

<table>
<tr><th></th><th>Correct trial</th><th>Incorrect trial</th></tr>
<tr><td>Item STM task
Question: Did both words appear in the list of words previously shown?</td><td>


</td><td>


</td></tr>
<tr><td>Order STM task
Question: Did both words appear in the list of words previously shown in this order?</td><td>


</td><td>


</td></tr>
</table>

Table 2: Overview of the item and order STM tasks with examples

The words for both tasks were drawn from a pool of 60 bisyllabic concrete words [7] and pseudo-randomly sampled, each one formed of five phonemes, used in an experiment by Majerus, Poncelet, Van der Linden, et al. (2006). This pool consisted of 30 pairs of words that differed by a single

[7] For more details on stimuli see Appendix A8.

phoneme and by a single letter, forming 30 minimal word pairs (e.g., legion – lesion, stable - staple). Mean lexical frequency based on adult experience was matched within the minimal word pairs: for the first and second words of the pairs mean lexical frequency was 49.93 (range: 0.61 – 482.77) and 49.05 (range: 0.91 – 410.26) respectively (Lexique 2 database, New, Pallier, Brysbaert, & Ferrand, 2004). Each of the 60 words of the stimulus set occurred exactly twice in both item and order STM conditions, with the restriction that the two words of a minimal pair could never occur together in the same trial, except for the negative probe trials in the item STM condition where one word of the pair occurred in the target list and the other in the probe array. There were an equal number of positive and negative probe trials, probing equally all item positions. Participants had to complete a total of 6 blocks, 3 blocks with the item STM tasks and 3 blocks with the order STM tasks. When participants started with an item STM block, they continued with an order STM block and vice versa, until they had completed all 6 blocks. Each block consisted of 25 trials and there were a total of 75 trials per condition.

4.2.2. Experimental Design

Four words were used in the item and order STM task since this is the number of items that can generally be kept in STM without exceeding participants' processing limits (Cowan, 2000; Glassman, 2003). Compared to behavioural experiments, the aim in ERP experiments is to keep all participants at a similar level of cognitive performance in order to get comparable results across participants. EEG collection was time-locked to the onset of each study word and the two probe words respectively.

In both tasks participants made their decision within 3000 ms by pressing the appropriate button with the index finger on their right hand (children had more time, 5000ms)[8]. Every study word as well as the probe words sent triggers to NetStation to facilitate the identification of event related potentials (ERPs).

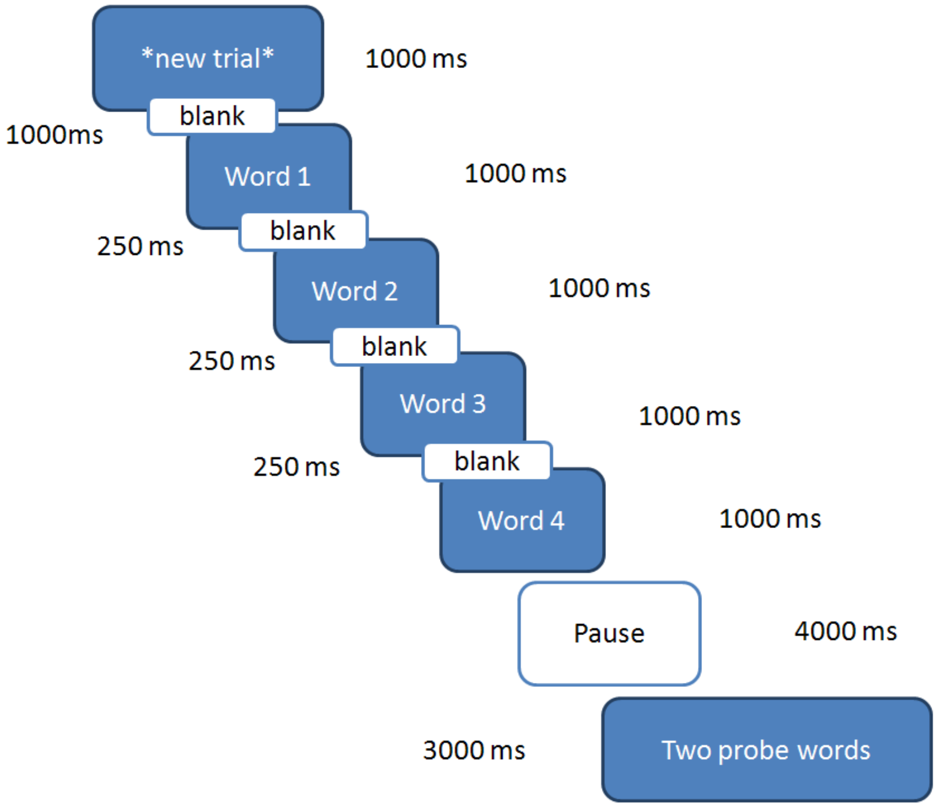


Figure 8: Experimental design of the ERP studies.

4.3. Analysis

Using Netstation software, the data were first filtered to eliminate environmental 'noise' (i.e. electrical noise from surrounding computer equipment) with a bandpass filter of 1-30Hz. Then, the data were visually explored and bad channels were marked. Artefact detection allowed us to detect 'noise' from channels and segments, e.g. muscle movements such as eye-blinks etc (± 100μV differential amplitude; eye blink ± 70μV). An automatic artefact rejection routine was utilized, and in addition each subject´s retained

[8] If participants needed more than 3000/5000ms to respond the next trial started automatically and nothing was recorded.

data were inspected off-line and any obviously deviant EEG waveforms were eliminated. Bad channels were then replaced by interpolation of data from ‘good’ neighbouring electrodes.

In the next step, data were segmented: Segments of EEG locked to the same stimuli were selected and reduced into two different categories: Waveforms triggered by order STM probe words and item STM probe words. The chosen time window for the segmentation was from -200ms before the stimuli onset (i.e., the onset of presentation of the two probe words that participants needed to respond to) until 1500ms post stimuli. A standard baseline correction was applied (see Luck, 2005, p. 236 for details), using -200ms to 0ms to compute the baseline in each segment.

In EEG each channel represents the difference between a certain electrode and (a) designated reference electrode(s). There is no standard position at which this reference is placed. However, it must be at a different position than the recording electrodes. Midline positions are often used because they do not amplify the signal in one hemisphere vs. the other. Another popular reference is a physical or mathematical average of electrodes attached to both earlobes, the tip of the nose, or the mastoids (little bone behind the ear). In our case, the outputs of all of the amplifiers were summed and averaged and this averaged signal was used as the common reference for each channel (this procedure is called off-line re-referencing). This procedure is commonly used in ERP-research with the EGI equipment and allows changes in the CPz channel to be detected.

This procedure was carried out on the EEG data from every single subject and single subject averages of each segment (= time window) for each category (i.e. item or order probe words) were created. This gave us the average waveform for each participant for the item and order STM response. Finally all participants’ averages were averaged together to create a grand average across all subjects.

In each participant´s data, those data that were too noisy, i.e. trials that had too many bad channels (criterion: average amplitude exceeds 200μV or channel has zero variance, eye blink and eye movement threshold criterion:

70μV), were excluded from analysis. Prior to statistical analysis data were screened and found to be normally distributed. After careful visual inspection, selected outliers were removed (see Krauledat, Dornhege, Blankertz and Müller, 2007, for details on rendering EEG data more robust by removing outliers).

For the P200 analysis, waveforms between 150 and 250 ms were analysed, for P300 waveforms between 250 and 350 ms, and for LPC, waveforms between 500 and 700ms.

5. Study 1: Monolingual Adults

As argued in Sections 4, 6, 7 and 8 of Chapter 1, behavioural studies have demonstrated dissociations between item and order STM – for example order STM but not item STM predicts vocabulary learning in ML speakers (for more details see e.g., Henson, Hartley, et al., 2003; Majerus, Poncelet, Elsen, et al., 2006; Poirier & Saint-Aubin, 1996). Recent fMRI studies also suggest item and order processing may activate different cortical areas in MLs (Henson, et al., 2000; Majerus, et al., 2007; Majerus, Poncelet, Van der Linden, et al., 2006; Marshuetz, et al., 2000).

As pointed out in Section 3 of this chapter, several researchers have shown the P200 component to relate positively to retrieval in short-term memory experiments (Chapman, et al., 1981; Friedman, et al., 1981; Taylor, et al., 1990). In a study by Gevins et al. (1996) the P200 was found to be enhanced during an order STM task (match each stimulus with a preceding stimulus occurring three positions before the match stimulus) compared to a control task (participants only had to press a button if an item had occurred before or not). In 1998, Dunn et al. investigated the relation of ERP components to complex memory processing using a “rote” serial-order (might reflect order STM) and an “elaborative” category memory task (might reflect item STM). They found that a P300 occurred particularly in the serial order task in the frontal areas. In 1992, Pelosi et al. used a digit probe identification task with 1, 3 or 5 aurally presented digits followed by a single probe digit. This task might reflect a mixture of item and order STM tasks. The authors found a late parietal positive wave (the authors call it P560) that occurred significantly more often in responses associated with larger memory sets and slow reaction times (RT), suggesting that its presence reflects subjective difficulty in performing a task. As pointed out before (see Section 3 this chapter) LPC might also index more elaborative processes based on information stored in long-term memory. On the basis of these findings larger P200, larger P300, and larger LPC are expected for order STM compared to item STM tasks.

5.1. Participants

20 monolingual native English speakers (8 male), right-handed, were recruited from the Sussex University community. Age ranged from 18 to 37 years, with a mean of 20.60 years (SD = 4.06 years). Minimum number of years of education was 12. Twelve additional participants had to be excluded due to technical problems during recording or excessive artefacts due to movement.

All participants gave their written informed consent prior to their inclusion in the study (see Appendix A1 for details) and completed a questionnaire to ensure they did not suffer from any neurological impairments (e.g. epilepsy, metal implants) or from any skin allergies, take medication for depression, have dyslexia or any other learning disabilities, have a cold or flu or were getting over a cold or flu at the time they intended to participate nor have suffered severe head injury in their lifetime (i.e. loss of unconsciousness for more than 30 minutes).

All subjects were paid for participation. The study was approved by the Ethics Committee of the School of Life Sciences of the University of Sussex.

5.2. Results

5.2.1. Behavioural Results

Monolingual adults differed significantly in accuracy rate between item and order recognition tasks (t(19)=3.39, p=.003): In the item task, they achieved an accuracy of 80% (Std.=9.23), in the order task 87% (Std.=6.70). They were not only better, but also significantly slower in the order task, compared to the item task (t(19)=2.65, p=.016).The average reaction time (RT) in the item task was 1576ms (Std.=208ms), in the order STM task 1664ms (Std.=238ms). This difference was expected due to the recruitment of serial order scanning processes which take time (see Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006). Refer to Figure 9 for graphs on reaction times and accuracy.

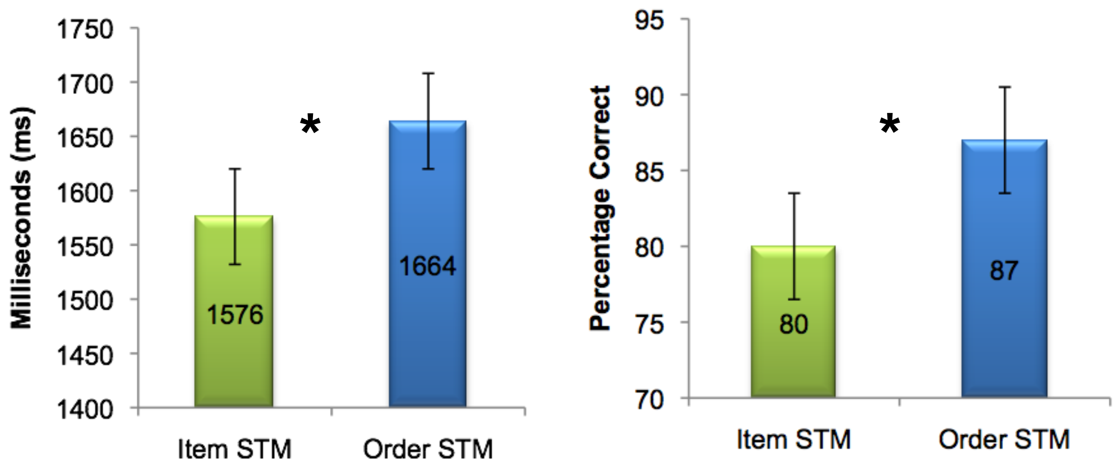


Figure 9: Reaction time (milliseconds) and accuracy (percentage correct) in item and order STM tasks in ML adults (*=p<.05)

5.2.2. Event Related Potentials

5.2.2.1. Visual Analysis of ERPs

The ERP grand mean waveforms for item and order verbal STM in response to probe word pairs for monolingual speakers for 9 selected electrodes are shown in Figure 10. Electrodes are labelled according to the 10-20 system (see Figure 10). Each electrode in the 10-20 system is allocated to an electrode on the 128 channel EGI net (for a description of correct electrode positioning according to the 10-20 system see Milnik, 2009). Figure 12 contains voltage maps computed by subtracting ERPs for item and order STM tasks. They were included to better visualize the scalp distribution of verbal STM effects at the three time points P200, P300 and LPC.

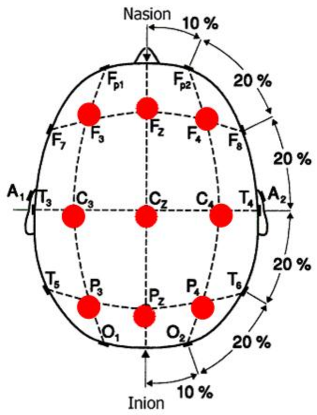


Figure 10: 10-20 System – The red electrodes are depicted for visual analysis in the graphs below.

As can be seen in Figure 11, the monolingual adult participants show a clear P200 in the left frontal electrode F3 (it can also be seen at Fz but is comparatively smaller) for both item and order STM. Order seems to elicit a stronger P200. However, the difference between the conditions is relatively small and does not show up on the voltage map (item STM ERPs subtracted from order verbal STM ERPs).

The P300 is also elicited in parietal regions (P3, Pz) but mainly for order STM. Also it can be noted, that it appears rather late (peaks at 350ms at Pz) compared to the item task where the P300 peaks earlier (at 300ms at Pz). For the P300, the voltage map shows differences between the conditions in parietal areas.

An LPC is strongly elicited in parietal areas with higher positivity in order STM tasks compared to item STM tasks and it is also order STM that shows stronger positivity in frontal and central areas. Similar to P300, differences between item and order tasks appear in the voltage map.

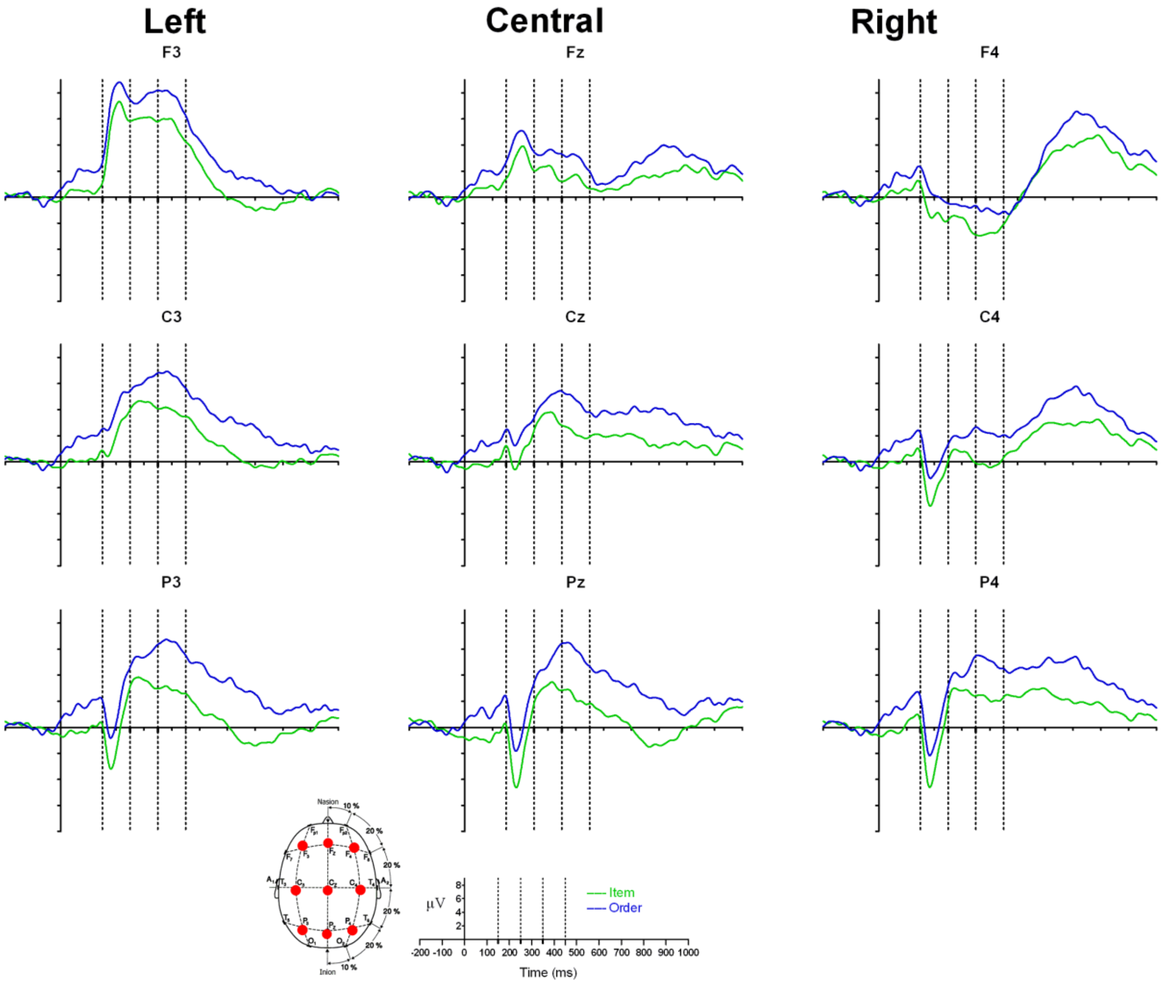


Figure 11: Waveforms for item and order STM in ML adults; positive plotted up

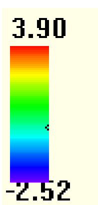
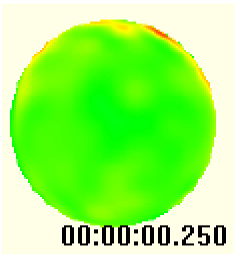
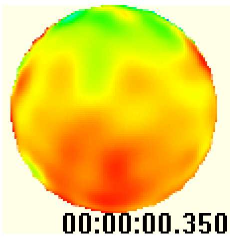
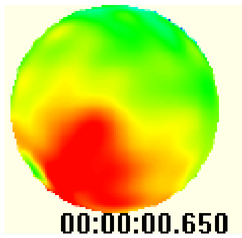
			
	P200	**P300**	**LPC**

Figure 12: Voltage maps computed by subtracting ERPs for item and order STM tasks for the three time points in ML adults.

5.2.2.2. Analysis of ERP Data

The P200, P300 and LPC mean amplitude data were analysed with a series of 3-way repeated measures ANOVAs. Within subject variables were memory task (item versus order), hemisphere (left versus right) and location (frontal versus parietal). Post hoc tests were then carried out for each recording site separately using paired t-test measures with Bonferroni corrections. Main effects of hemisphere and location are not of interest to us as we are interested in task differences and consequently these data will not be discussed further (this form of analysis is common practice in ERP studies, for examples see e.g., B. R. Dunn, et al., 1998; Marshall, Drummey, Fox, & Newcombe, 2002).

P200 data. No significant differences in the neuro-electrical correlates for item and order STM were found for the P200 area (150ms to 250ms post stimuli) in monolingual adults when looking at mean amplitude.

P300 data. For the P300 area (300ms to 400ms post stimuli) a significant task by location effect was found for mean amplitude, $F(1, 19)=5.231$, $p=.034$. Both item and order STM elicited less positivity in the front and more positivity in parietal parts of the brain, but the difference in positivity between parietal parts of the brain compared to frontal parts was greater for order STM compared to item STM (see Figure 13 for details). Post hoc paired t-tests comparing order vs. item STM in the four electrode sites anterior right, anterior left, parietal right and parietal left revealed that order STM (mean: 6.38, SD: 9.07) showed a marginally more positive amplitude compared to item STM (mean: 3.49, SD: 3.50) in the right parietal part of the brain, $t(19)=1.896$, $p=.073$. No significant difference between the tasks was found in frontal areas and the left parietal area (all p’s < 0.3).

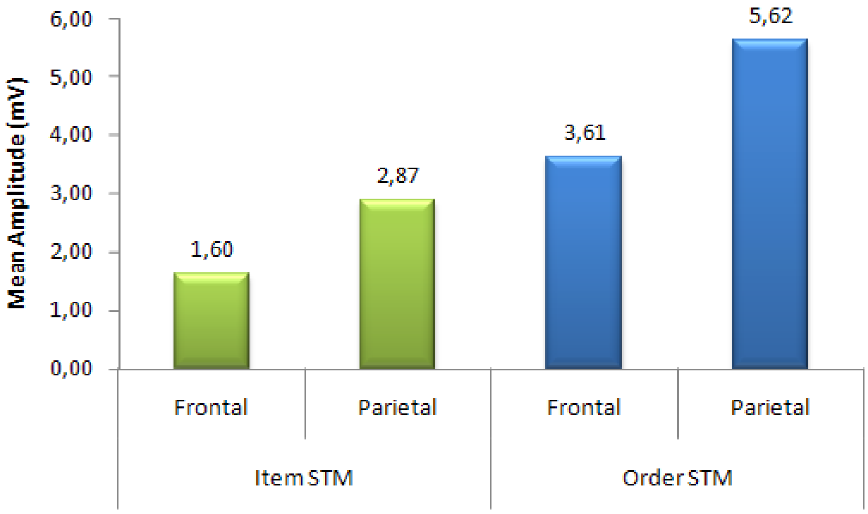


Figure 13: Task by Location amplitude effect at P300 in ML adults

LPC data. An ANOVA for mean amplitude between 500 and 700ms post stimuli revealed a significant main effect of task, $F(1, 19)=6.228$, $p=.022$, with order STM eliciting overall more positivity compared to item STM across the whole head, see Figure 14 for details.

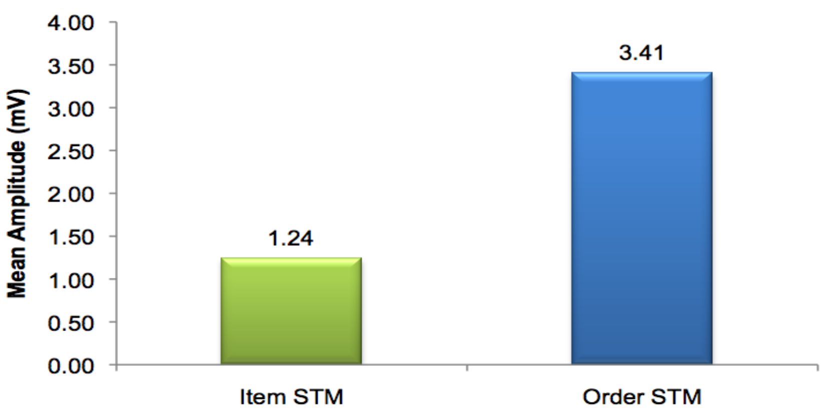


Figure 14: Main effect of Task in amplitude at LPC in ML adults

Also, a significant task*location effect was found, $F(1, 19)=8.361$, $p=.009$. Order STM elicited overall more positivity compared to item STM and showed relatively more positivity in parietal areas compared to frontal areas, while item showed relatively more positivity in frontal areas compared to parietal areas, see Figure 15 for details. Post hoc paired t-tests comparing order vs. item STM in the four electrode sites anterior right, anterior left, parietal right and parietal left revealed significant effects of higher positivity in order STM compared to item STM in parietal areas, both left, $t(19)=2.651$, $p=.016$, and right, $t(19)=2.728$, $p=.013$. No significant difference between the tasks was found in frontal areas (all p's < 0.4).

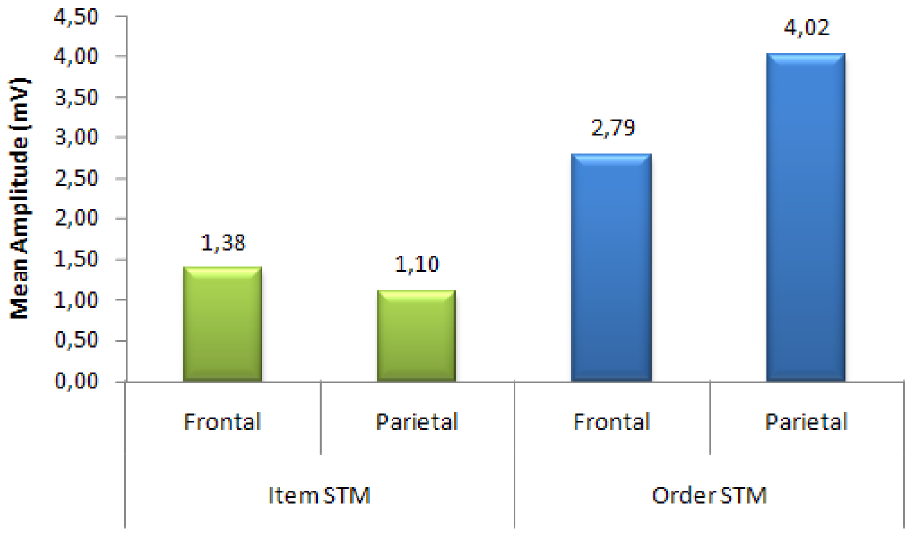


Figure 15: Task by Location amplitude effect at LPC in ML adults

5.3. Interim Discussion

As hypothesised, there appear to be some differences in the nature of the ERPs evoked by item versus order memory tasks. In particular, MLs generated larger P300 and LPC amplitudes in order STM compared to item STM tasks.

The amplitude of the P300 component was greater in the order recognition task compared to item STM. In addition, both item and order STM elicited more positive P300 amplitudes in parietal parts of the brain as compared to the front part of the brain. It has been argued that the P300 is related to context updating in working memory (Donchin, 1981; Fabiani et al., 1986; Nittono et al., 1999; Howard & Polich, 1985; Blumhardt, 1996; Pelosi et al., 1992, 1998; Starr & Barrett, 1987; Key, Dove &Maguire, 2005; Polich, 2007). Therefore one possible interpretation of the present results is that order STM tasks involve more context-updating than when remembering the item identity alone. During order STM tasks the position of each item has to be remembered in addition to remembering the item identity of each item. This could indicate that the order STM task is comprised of two task components, (e.g., a stimulus identification component as found in item STM and a serial position component) and that these two components share common attentional and processing resources to which P300 is related (see e.g., Kok, 1997; Nittono, et al., 1999). Recent STM models also propose that common resources are used for serial order information and item identity information (Burgess & Hitch, 1999; Gupta, 2003; Majerus, 2008). An increased positivity between 500 and 700ms at parietal sites for order STM was predicted in our experiment (see e.g., Gibbons, Brandler, & Rammsayer, 2003; Pelosi, et al., 1992). This prediction was supported: Order STM elicited overall higher positivity in parietal areas compared to the item STM task. The LPC has been found to be larger with bigger memory sets and also when participants have slower task reaction times suggesting that its presence might reflect subjective difficulty in performing a task (Pelosi et al., 1992). Indeed, ML adults were significantly slower in order STM tasks compared to item STM tasks. However, they performed better in order STM tasks. This raises the question whether or not the order STM task might have been harder or easier for them (as the two behavioural measures, time and accuracy, go in different directions this behavioural difference is not clear). Maybe the order STM task demanded additional cognitive demands that made participants work more slowly but more accurately on the order STM task. It has also been suggested that the LPC might index relatively simple lexical or semantic encoding (Besson, Kutas, Van Petten, 1992; Paller & Kuttas, 1992; Van Petten et al., 1991; Dunn et al., 1998). However, it is unlikely that the involvement of these processes differed across the two tasks as they controlled for word frequency, lexicality and semantics (i.e. word type). Importantly, Turconi, Jemel, Rossion and Seron (2004) investigated electrophysiological evidence for differential processing of numerical quantity and order. 25 native French adults performed a quantity task (classifying numbers as smaller or larger than 15) and an order task on the same material (classifying numbers as coming before or after 15), as well as a control order task on letters (classifying letters as coming before or after M). They showed that order tasks elicited higher evoked potentials in right parietal areas, relative to left parietal areas in the P200 time window. Similar results were found in our data in the P300 time window where order STM showed (marginally) more positive amplitude compared to item STM in the right parietal part of the brain. This could point further to a right parietal location for serial order STM processing (see also the next chapter with a study using TMS for a detailed discussion). Note that this is just one possible interpretation as no source localisation was used to confirm the ERPs reflected on the scalp also originated from right parietal areas.

Taken together, no amplitude differences between item and order STM tasks were found in the P200 time window. Order STM showed higher positive amplitudes than item STM in P300 and LPC time windows. A possible explanation for this finding is that order STM demanded more working memory capacity compared to item STM.

6. Study 2: Bilingual Adults

As with ML speakers, differences between item and order STM processing have been demonstrated in BL speakers by a number of behavioural studies (see Chapter 1, Section 6). For example, only a serial order STM task but not an item STM task predicted independent variance in a paired associate word-nonword learning task in BL participants (Majerus, Poncelet, et al., 2008; also see Section 7 in Chapter 1). In addition, a recent fMRI study suggests that specific cortical regions are active during item and order STM tasks in high proficient BL participants (Majerus, Belayachi, et al., 2008). These regions are assumed to reflect the updating and grouped rehearsal of serial order information (see Majerus, Poncelet, Van der Linden, et al., 2006) while item STM activated brain areas associated with phonological and orthographic processing respectively (Binder, et al., 2000; Bolger, et al., 2005; Majerus, Poncelet, Van der Linden, et al., 2006; Scott, et al., 2000).

No ERP studies with BL speakers have yet been conducted investigating item and order STM processes. ERP studies with BLs generally focus on switching between L1 and L2 or word processing but not on memory. Hence, the study will be exploratory. From the review above it can be predicted that high proficient BL speakers will show differences in memory-related neural ERP patterns (i.e. P200, P300 and LPC) for item and order STM.

6.1. Participants

19 fluent English-German bilingual speakers (6 male), all right-handed, were recruited from online platforms for Germans living in Brighton, UK, and for the Sussex University community. Age ranged from 20 to 30 years, with a mean of 23.58 years (SD = 3.45 years). Minimum number of years of education was 12 years. Nine additional participants had to be excluded due to an English age-score of below 16 on the British Picture Vocabulary Scale (BPVS).

The same medical exclusion criteria were used as for ML participants (see Appendix A1 for details).

A language questionnaire was given to each participant prior to taking part in the experiment (see Appendix A2 for details). 17 participants were originally from Germany, one from Switzerland and one from Austria, two of the participants were bilingual from birth, both having an English speaking mother and a German speaking father. Other languages spoken by the participants were French, Spanish, Italian, Latin, Arabic, Japanese, Swedish and Tagalog. However, all participants reported not being fluent in a language other than English and German. On a Likert scale they rated their German knowledge 6.9 (range: 6-7) and their English knowledge 6.4 (range: 5-7; 7 being the best and 0 being the worst). They had lived on average 3 years in an English speaking country (range: 0.4-12) and had started to learn English at age 8.6 (range: 0-15 years). They had learned English as a Second language on average for 7.8 years (range: 3-13). An inclusion criterion for the group was an English age of above 16 on the British Picture Vocabulary Scale (BPVS). Average percentage on the BPVT was 87% (range: 63-99), the average English age equivalent was 16.7 years (17 being the highest possibility in the test). They also had to complete the Peabody Picture Vocabulary Test (PPVT) in German and showed an average of 95.19 (range: 63-99). To test active vocabulary participants had to name pictures from the Snodgrass and Vanderwart (1980) pictures in both English and German (see Appendix A3 for picture naming stimuli). Participants were able to name 93.25% of the pictures in English correctly (range: 67-100) and 98% of the pictures in German (range: 88-100).

The method was identical to that from the previous study with ML adults. Like in the previous chapter, prior to statistical analysis data were screened and found to be normally distributed. After careful visual inspection, selected outliers were removed (see Krauledat, Dornhege, Blankertz and Müller, 2007, for details on rendering EEG data more robust by removing outliers).

The study was approved by the Ethics Committee of the School of Life Sciences of the University of Sussex.

6.2. Results

6.2.1. Analysis I: Item and Order Processing in BL Adults

6.2.1.1. Behavioural Results

Bilingual adults did not differ in accuracy rate between item and order recognition tasks: In the item task, they achieved an accuracy of 86% (Std.=7.31), in the order task 87% (Std.=11.05). However, they were slower in the order task, compared to the item task (t(18)=4.658, p<.001): The average reaction time (RT) in the item task was 1562ms (Std.=197ms), in the order STM task 1691ms (Std.=226ms). This difference was expected due to the recruitment of serial order scanning processes (see also Majerus et al., 2006). Refer to Figure 16 for graphs on reaction times and accuracy.

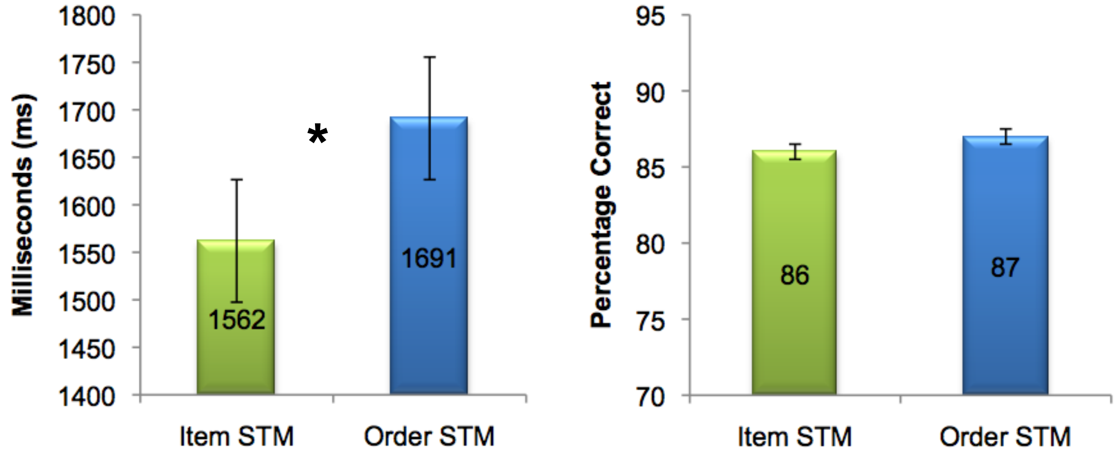


Figure 16: Reaction time (milliseconds) and accuracy (percentage correct) in item and order STM tasks in BL adults (*=p<.001)

6.2.1.2. Event Related Potentials

6.2.1.2.1. Visual Analysis of ERPs

The ERP grand mean waveforms for item and order verbal STM for bilingual speakers are plotted in Figure 17. Figure 18 contains voltage maps computed by subtracting ERPs for item and order STM tasks. They were included to better visualize the scalp distribution of verbal STM effects at the three time points P200, P300 and LPC.

As can be seen in these figures, the bilingual adult participants show a clear P200 in the left frontal electrode F3 (it can also be seen at Fz but relatively smaller) for both item and order STM. The waveforms are relatively similar for both item and order verbal STM. Also in the voltage map (item STM ERPs subtracted from order verbal STM ERPs) no differences were detected (the negativity in the very front might reflect differences in eye blinks and can be disregarded.)

The P300 is also elicited in parietal regions (P3, Pz, P4), similarly for both item and order. Here, the voltage map also does not show differences between item and order in parietal regions.

LPC is only somewhat elicited in parietal areas, again similarly in both item and order STM tasks. In frontal regions item STM seems to elicit more positivity compared to order STM and these differences can also be seen in the voltage map with subtracted waveforms indicating differences between item and order tasks (item more positive compared to order STM ERPs).

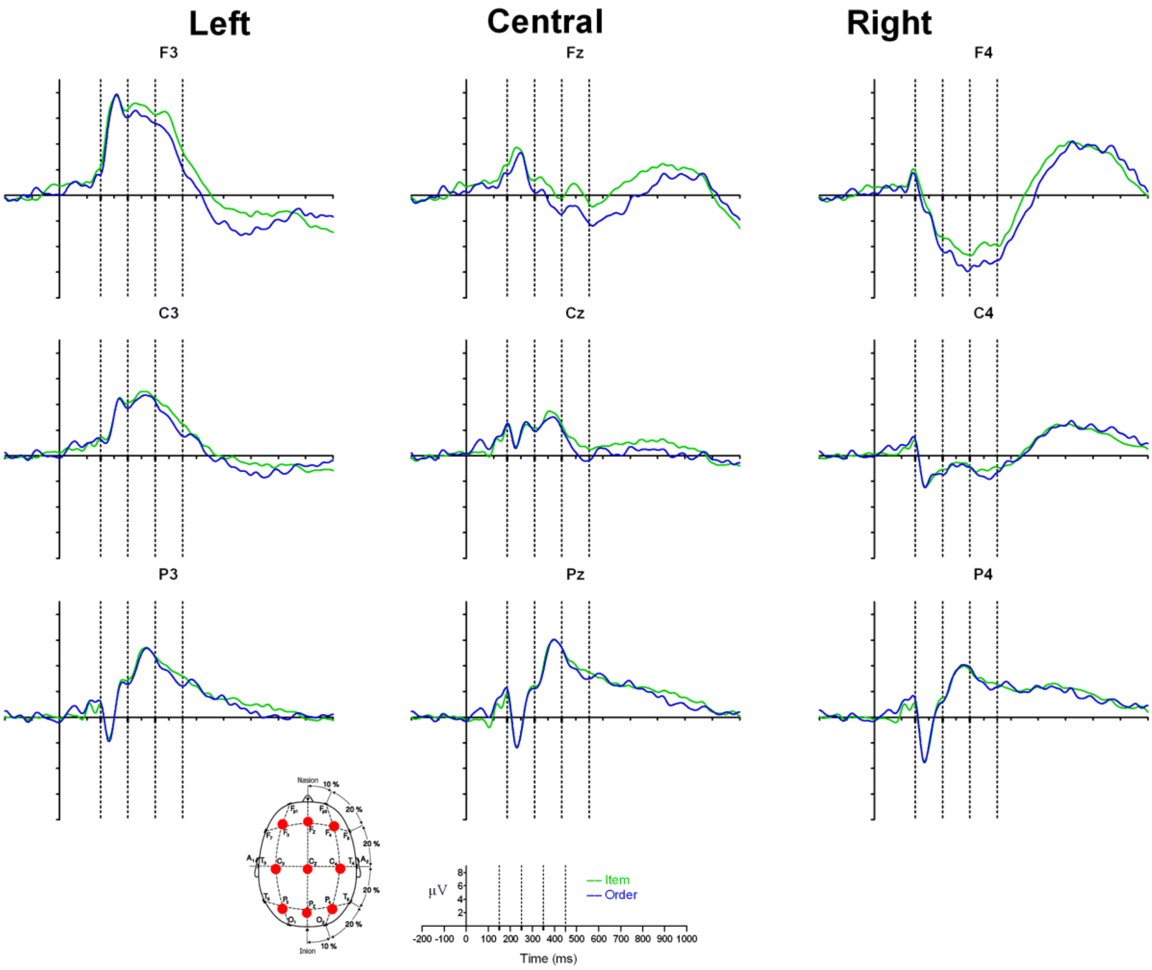


Figure 17: Waveforms for Item and Order STM in BL Adults

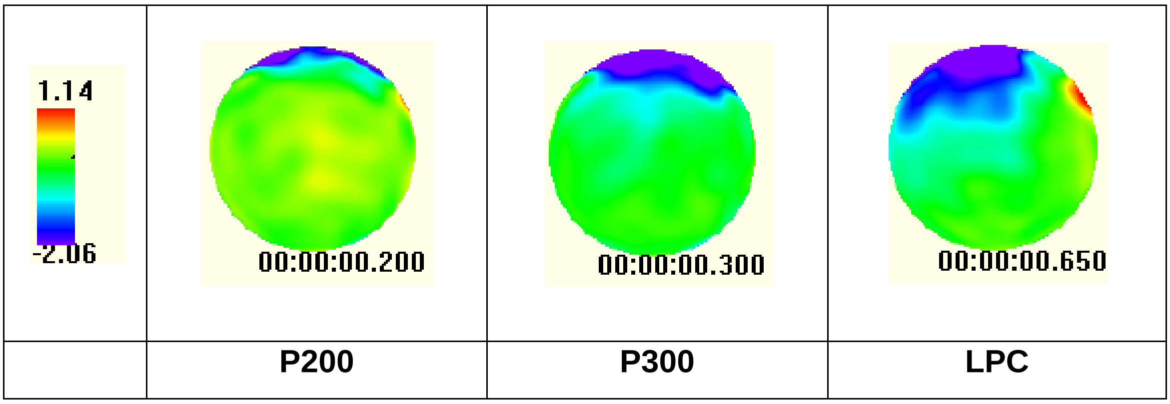


Figure 18: Voltage maps computed by subtracting ERPs for item and order STM tasks for the three time points in BL adults.

6.2.1.2.2. Analysis of ERP Data

Analysis was carried out on the same principles as with ML adults.

P200 data. No significant differences in the neuro-electrical correlates for item and order STM were found for the P200 area (150ms to 250ms post stimuli) in bilingual adults when looking at mean amplitude.

P300 data. No significant differences in the neuro-electrical correlates for item and order STM were found for the P300 area (250ms to 350ms post stimuli) in bilingual adults when looking at mean amplitude.

LPC data. An ANOVA for mean amplitude between 500 and 700ms post stimuli revealed a significant task*location interaction, F(1,18)=9.249, p=.007, with order STM eliciting similar positivity to item in parietal regions, but a less positive mean amplitude in order STM compared to item STM in frontal regions, see Figure 19 for details. A paired t-test for mean amplitude revealed a trend towards more negativity in order STM (mean: -2.14, SD: 2.57) compared to item STM (mean: -1.22, SD: 2.85) specifically in left frontal brain areas, t(18)=2.008, p=.06.

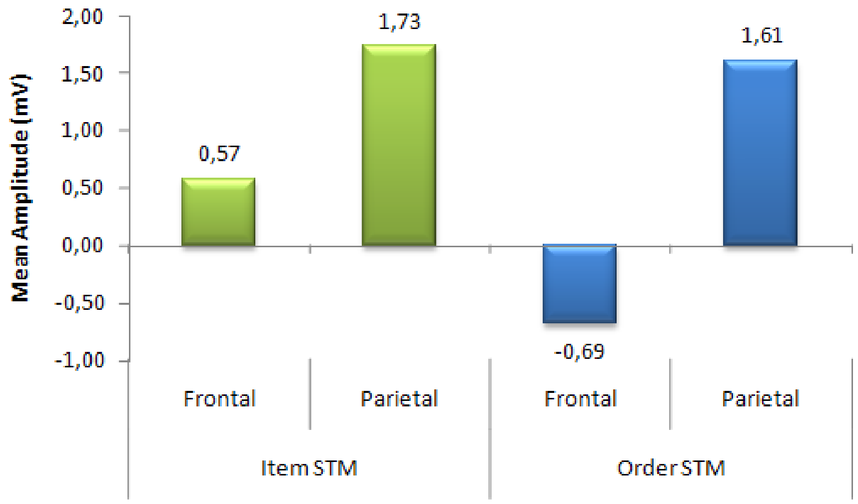


Figure 19: Task by Location amplitude effect at LPC in BL adults

6.3. Interim Discussion

For BL speakers no significant differences in the neuro-electrical correlates for item and order STM were found for P200 and P300. A significant task by location interaction only emerged at the later LPC component: Order STM elicited similar positivity to item STM in parietal regions, but less positive mean amplitude in frontal regions. Taken together, the neuro-electrical correlates for item and order STM in BL participants show few differences between the tasks.

One possible explanation for why item and order STM tasks were processed rather similarly in BL adults lies within the tasks themselves. It has been shown that while the order STM tasks seem to tap into areas assumed to reflect the updating and grouped rehearsal of serial order information (Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006), the item STM task activated areas associated with phonological and orthographic processing respectively (Binder, et al., 2000; Bolger, et al., 2005; Scott, et al., 2000). As BLs seem to process both item and order STM tasks relatively similarly, it indicates that they use similar strategies to recall both item and order information. They might use their order STM more also while performing the item STM task or the other way around[9]. When performing tasks in their second language they might have to activate areas associated with phonological and orthographic processing more, which might mask differences in the neuro-electrical correlates for item and order STM. While ML English speakers could simply concentrate on memory strategies in their only language, BL speakers might have activated several other processes (e.g. translation or uncertainty about pronunciation, etc.) in addition to the required memory processes. This again could have led to more item-STM-related neuro-electrical correlates also during the order STM task. Some support for this hypothesis is provided by a study of Majerus, Poncelet, Van der Linden, et al. (2006) who found that low proficient BLs activated areas known to be

[9]Note that just using item information will not enable order STM tasks to be performed properly.

significantly involved during item STM processing in monolinguals while performing the order STM task. However, all participants in this study were highly fluent bilingual speakers so this interpretation of the finding might not be applicable to them.

This hypothesis can explain the finding of lower LPC amplitude in order STM in parietal regions. LPC in parietal regions is linked to recollective processes (Rugg & Curran, 2007) which seem to be similar for item and order STM in BL participants, while LPC in the frontal cortex might indicate relatively simple lexical or semantic feature encoding (see e.g., B. R. Dunn, et al., 1998; Paller & Kutas, 1992; Smith, 1993) which seems to be different for item and order STM in BL speakers. The difference in item STM compared to order STM in BL participants could be due to the processing of words in a second language. As both tasks were controlled for linguistic features, it is highly unlikely that BL participants were processing the words in the two tasks differently in terms of lexical or semantic encoding.

LPC has also been found to index more elaborative processes based on information stored in long-term memory (see also Besson, et al., 1992; Paller & Kutas, 1992; Van Petten, et al., 1991; Van Petten & Senkfor, 1996). It is more likely that the LPC reflects more elaborative processes which need to be activated during item STM tasks in BL speakers as reflected in higher frontal amplitude rates in item STM compared to order STM. An enhanced LPC in high proficient BL English-Spanish bilinguals was also found in an ERP study by Alvarez and Holcomb (1999). They examined ERP repetition effects in an English-Spanish bilingual priming paradigm in which stimulus repetition was incidental to the task employed. Words were visually presented in a constant stream (L1 or L2) and immediate repetitions within this stream occurred either within a language (L1/L1 or L2/L2) or between languages (L1/L2 or L2/L1). Only the L1/L2-condition (e.g., dog-perro) revealed an enhanced LPC. The authors suggest that their results indicate that there are different retrieval demands on memory when reading in a first or second language. The enhanced LPC in item STM in the described study could hence indicate a stronger involvement of language-related sub-processes which might affect the retrieval of item STM but not as much the retrieval of order STM. The focus during the item STM task is on item identity (i.e., if the same words had been presented before or not) which indeed is more likely to activate phonological and orthographic features of the words compared to the order STM task, where simply the position of the items needs to be recalled (see also Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006).

To help clarify the underlying neuro-electrical correlates for item and order STM further, the BL group will now be compared to the ML speakers.

6.3.1. Analysis II: Comparison of Monolingual and Bilingual Adults

As argued previously, if order STM is related to language learning capacity, it is possible that BL speakers will process order STM differently to ML speakers, as BLs have acquired two languages as opposed to ML speakers who only acquired one. Very few behavioural studies have investigated differences between BL and ML speakers in item and order STM tasks. However, some studies suggest that BL speakers outperform ML speakers on order STM tasks (see e.g., Bialystok & Feng, 2009; Feng, Bialystok, & Diamond, 2009; Teubner-Rhodes, et al., 2011) and to foreshadow the results of a later chapter in this thesis, BL children outperformed ML children in an order STM tasks but not an item STM task (see Chapter 4 for details). This could suggest that order STM tasks could be easier for BL participants. This advantage of BLs could be reflected in the P300 and LPC components: In an ERP study Nittono et al. (1999) found that the P300 increased as task demands increased and suggested that P300 might reflect individual differences in working memory capacity (for more details see Section 5.3. this chapter). Based on behavioural data, it could be expected that BL participants might show lower P300 in order STM compared to ML speakers. LPC is thought to index reconstructive or recollective processes reflecting more elaborative processes based on information stored in long-term memory. This might take up more neural activation in MLs compared to BLs order STM as reflected in behavioural data where BL speakers outperformed ML speakers in order STM tasks. Importantly, LPC has been found to be larger in bigger memory sets and with slower reaction times, suggesting that its presence might reflect subjective difficulty in performing a task (Pelosi et al., 1992). Hence, BLs are expected to show lower LPCs in order STM compared to ML speakers. As only highly proficient English/German BL adults were permitted to take part in this study, item STM is expected to be similar in both groups. This analysis was done to investigate the possible distinct neural signatures of item and order STM tasks in ML and BL speakers given what might be expected based on behavioural results. For more details please refer back to Section 1 in this Chapter.

6.3.1.1. Behavioural Results

Two-way mixed ANOVA (2x2) with memory task (item versus order) as within subject variable and group (monolingual versus bilingual) as between subject variables showed a main effect of task on accuracy, $F(1,37)=10.330$, $p=.003$. Participants overall achieved higher accuracy in order STM tasks (mean=87% correct, SE=.015) compared to item STM tasks (mean=83% correct, SE=.013). A marginal task by group interaction effect was found, $F(1,37)=3.474$, $p=.07$, with ML item accuracy rates being the lowest (mean=80% correct, SE=.019) followed by BL item accuracy rates (mean=86% correct, SE=.019). Order STM accuracy scores were comparable with 87% correct for both MLs (SE=.020) and BLs (SE=.021). See Figure 20 for details. Importantly no main effect of group was found.

In reaction times, a significant main effect of task was found, $F(1,37)=24.898$, $p<.001$, with item STM showing overall faster reaction times (mean=1569ms, SE=32ms) compared to order STM (mean=1678ms, SE=37ms). No interaction with group was found for reaction times.

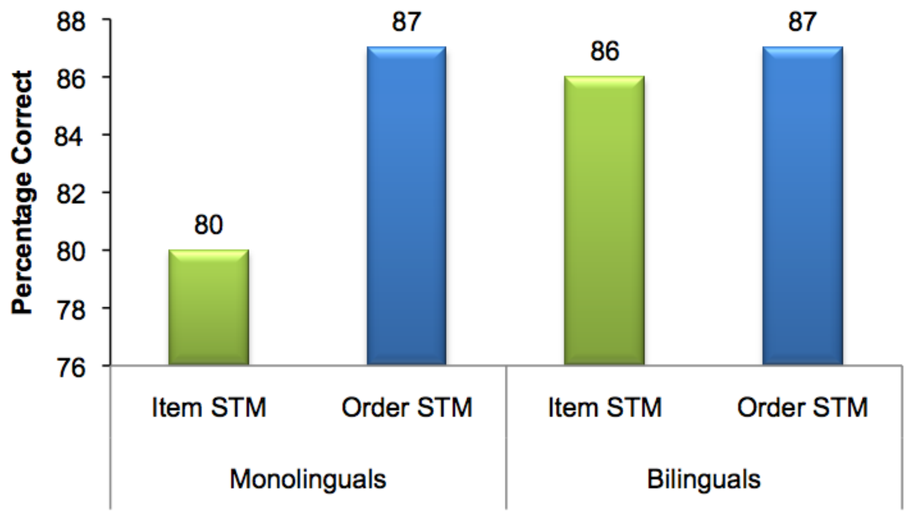


Figure 20: Accuracy in item and order STM tasks in ML and BL adults

6.3.1.2. Event Related Potentials

6.3.1.2.1. Visual Analysis of ERPs

The ERP grand mean waveforms for item and order verbal STM for monolingual and bilingual speakers are plotted in Figure 21. In BLs the waveforms in the P200 in left frontal electrodes are relatively similar for both item and order STM, compared to monolinguals where order STM seems to elicit a stronger P200. The P300 was elicited in both groups in parietal regions, again, with more differences in ML speakers with order showing a stronger P300 with a later peak compared to item STM. LPC in ML speakers elicited higher positivity in order STM in parietal areas compared to similar activity in BL speakers. In frontal regions, order showed stronger positivity in MLs while it was item that elicited stronger positivity in BL speakers.

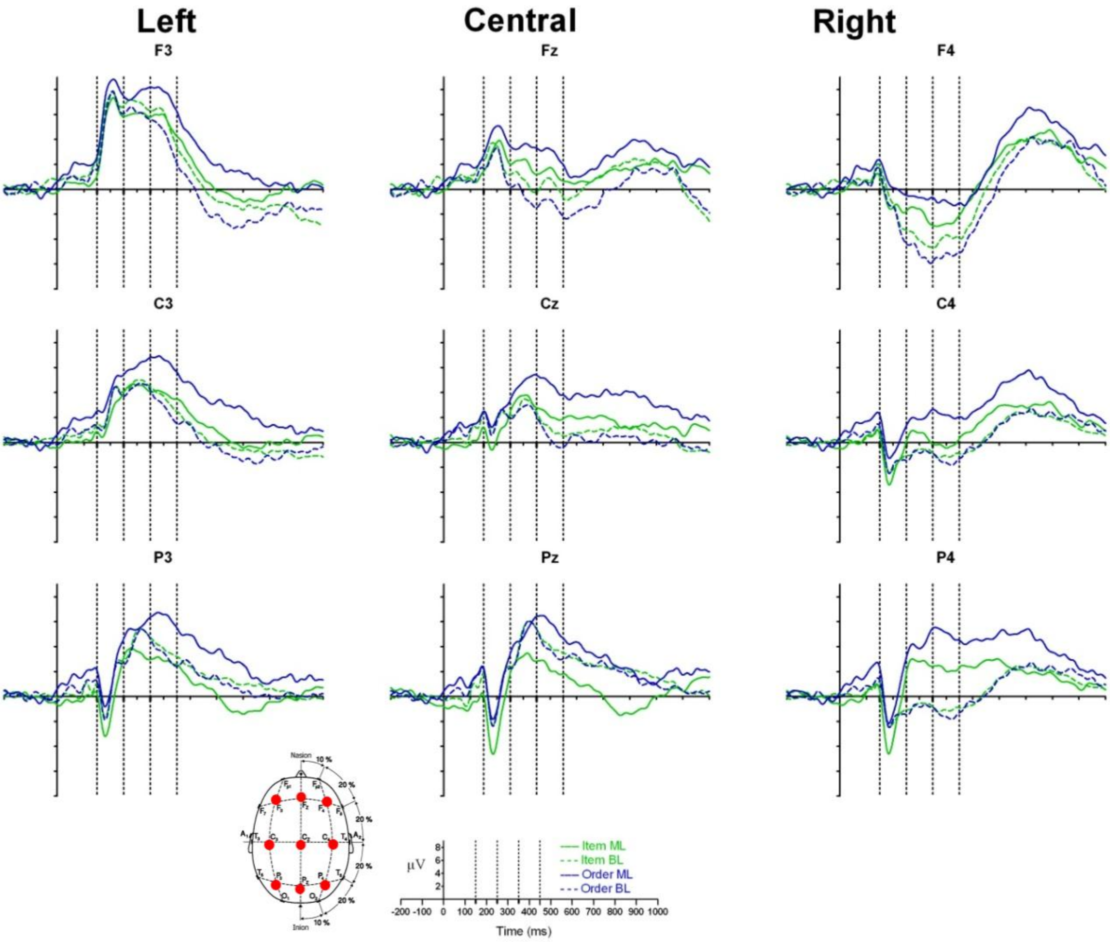


Figure 21: Waveforms for item and order STM in ML and BL adults

6.3.1.2.2. Analysis of ERP Data

The P200, P300 and LPC mean amplitude data were analysed using 4-way ANOVAs with a mixed (2x2x2x2) design. The between subject variable was group (ML or BL), within subject variables were memory task (item versus order), hemisphere (left versus right) and location (frontal versus parietal). Only statistically significant interactions involving areas of interest will be reported here. Post hoc tests were then carried out for each recording site separately using paired t-test measures with Bonferroni corrections. Main effects of hemisphere and location are not of interest to us as we are interested in task differences and consequently these data will not be discussed further (as pointed out before, this form of analysis is common practice in ERP studies, for examples see e.g., B. R. Dunn, et al., 1998; Marshall, et al., 2002).

P200 data. No significant difference between groups was found for the P200 area (150ms to 250ms post stimuli) when looking at mean amplitude.

P300 data. No significant difference between groups was found for the P300 area (250ms to 350ms post stimuli) when looking at mean amplitude.

LPC data. The ANOVA revealed a significant task*group interaction in amplitude, 500 to 700ms post stimuli, F(1,37)=7.527, p=.009. Order STM showed relatively more positivity in ML speakers compared to BL speakers, but item STM did not, see Figure 22 for details.

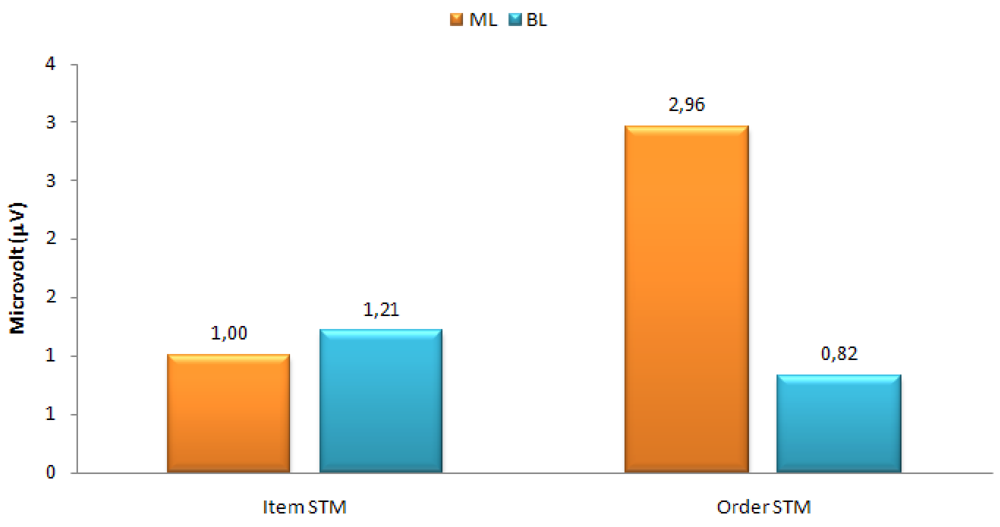


Figure 22: Task by Group effect in mean amplitude 500 to 700ms post stimuli when comparing ML and BL adults

To investigate which cortical areas showed the biggest group differences in amplitude level in item and order STM tasks, a post-hoc two-way ANOVA using Bonferroni correction with a mixed (2x8) design, with group (ML or BL) as between subject variable and task location (Item STM Front Left, Item STM Front Right, Item STM Parietal Left, Item STM Parietal Right, Order STM Front Left, Order STM Front Right, Order STM Parietal Left, and Order STM Parietal Right) as within subject variable was conducted. The analysis revealed significant differences between groups 500 to 700ms post stimuli for the order STM task only. No differences were found for the item STM task. Order STM showed significant amplitude differences between groups in frontal left areas, $F(1,37)=4.428$, $p=.042$ and a marginal effect in parietal right areas, $F(1,37)=2.934$, $p=.095$, see Figure 23 for details of the effect in frontal areas.

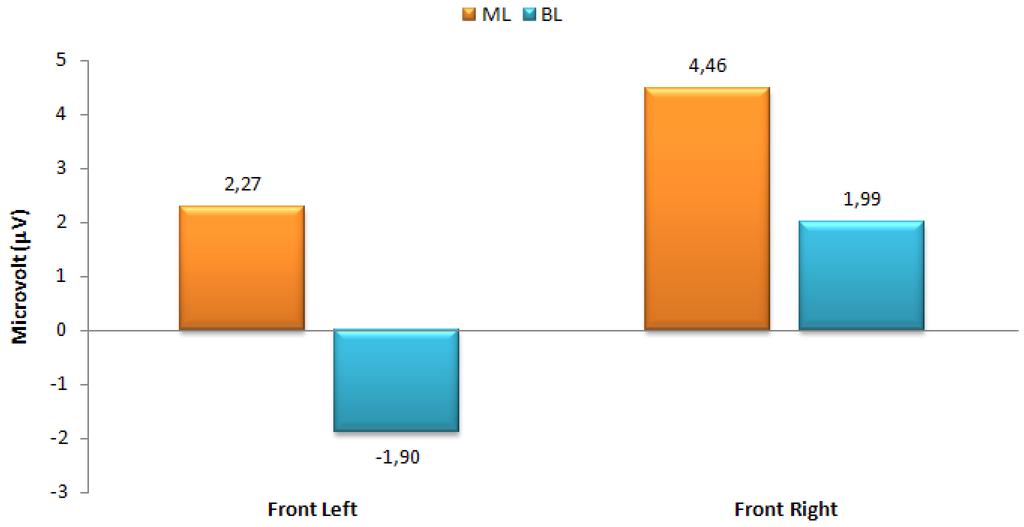


Figure 23: Amplitude differences in order STM task 500-700ms when comparing ML and BL adults

6.3.1.3. Interim Discussion

Taken together, no differences in patterns for neuroelectric activity in item and order STM tasks were found for the P200 and P300 components, both important ERP components for STM. This suggests some form of similar processing of item and order STM in BL and ML adults.

Amplitude differences only emerged after 500ms post stimuli and only in the order STM condition, not in the item STM condition. ML participants showed higher peak amplitudes for order STM, especially in parietal right and frontal left areas, compared to BL participants. This finding confirms the hypothesis that order STM shows different patterns for neuroelectric activity in ML and BL speakers. Interestingly, this difference was significant in the right parietal area, an area that previously has been pointed out to locate serial order STM processing (Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006; Turconi, et al., 2004).

As pointed out above, order STM is an especially critical determinant of language learning capacity (Jefferies, et al., 2006; Leclercq & Majerus, 2010; Majerus, Belayachi, et al., 2008; Majerus, Heiligenstein, et al., 2009; Majerus, Poncelet, Elsen, et al., 2006). The current finding strengthens the claim that order STM but not item STM is related to language learning capacity or alternatively to a lexical phonological store which is broader in BL speakers than in ML speakers. For example the word ‘dog’ in English consists of three phonemes in a specific order but knowing other words such as ‘chien’ or ‘Hund’ adds other phoneme-sequences for one semantically identical word. In addition, BLs are using the grammar and sentence structure of two languages which might also lead to different patterns for neuroelectric activity in order STM compared to ML speakers. Another reason why MLs show higher amplitudes in order STM tasks than BLs might lie within the language they speak: English is more rigid in its sentence structure and does not allow the flexibility of changing order as much as German. Hence German/English BLs can train and develop their order STM in many ways (i.e., flexible use of phonological sequences and language sentence structures) while ML English speakers cannot.

In a recent fMRI study, Majerus, Belayachi, et al. (2008) found that high and low bilinguals activate different brain regions for order STM and item STM (for a detailed description please refer back to Section 8.2. of Chapter 1). To sum up their findings, a functional network for order memory involving left IPS, right IPS and right superior cerebellum was found in the high proficiency group, whereas the low proficiency group showed enhanced activation in the left IPS and bilateral superior temporal and temporo-parietal areas, regions known to be activated during item STM processing in monolinguals (see Majerus, Poncelet, Van der Linden, et al., 2006). The authors suggest that low proficiency bilinguals activate STM networks for order in a less efficient manner than high proficient bilinguals. The authors suggested that this may explain the poorer storage and learning capacity for verbal sequences in low proficient bilingual speakers. The higher amplitude of MLs in the order STM task compared to BLs could further strengthen this claim, provided LPC reflects recollection (B. R. Dunn, et al., 1998; Paller & Kutas, 1992; Smith, 1993) or more elaborative processes based on information stored in LTM (see also Besson, et al., 1992; Paller & Kutas, 1992; Van Petten, et al., 1991; Van Petten & Senkfor, 1996). Wolk et al. (2009) investigated ERP correlates of recognition memory. They were interested in the effect of age and performance. In their study they compared young adults with elderly subjects who had to perform a word recognition memory task. Participants saw a list of words and then had to judge whether a word in the test list had been in the list before or not. LPC (the authors talk about late frontal effect, LFE, 500-700ms post stimuli) was increased in the older adults compared to the younger adults, and additionally was most prominent in the poorer performing older participants. The authors suggest that weak memory retrieval may lead to an enhanced LFE in the service of additional retrieval attempts. This finding could be reflected in our study with MLs showing higher amplitude levels in order STM compared to BL speakers. Even though, BLs did not outperform MLs in the task in this study[10], to foreshadow the results of a later chapter in this thesis, BL children

[10] Note that the task in this study was not designed to compare ML and BL speakers at behavioural level, i.e. participants only had to remember 4 items as the task was designed to be manageable in order to use as many trials as possible to analyse using ERPs.

outperformed ML children in an order STM tasks but not an item STM task (see Chapter 4 for details). Further evidence of BL adults and children outperforming ML adults and children has also been found in other studies (Bialystok & Feng, 2009; Feng, et al., 2009; Teubner-Rhodes, et al., 2011) even though the finding remains under debate (e.g. see Namazi & Tordardottir, 2010)

This raises the question whether the LPC amplitude in order STM can be manipulated by the amount of language knowledge, or in other words the complexity of the lexical phonological network. If so, it can be assumed that the LPC amplitude in order STM develops parallel to language knowledge, i.e. ML participants show highest LPC, followed by low proficient BLs, with high proficient BLs showing the lowest LPC, and multilingual speakers might show an even lower LPC for order STM tasks. Unfortunately this study cannot directly address this question because mainly high proficient BLs were tested. Future research could look into this further by conducting a follow up study investigating low proficient (English/German) BL speakers and trilingual speakers (of German/English and another language). Note that it would be important test all participants in the same language as language itself might influence order STM (i.e. German shows a more flexible language structure than English which could influence order STM performance).

In addition, the differences between monolingual and bilingual speakers might be due to the fact that bilinguals process words in their second language differently to words in their first language (i.e., van Heuven & Dijkstra, 2010). However, this is less likely as BL speakers only show different patterns for neuroelectric activity in order STM but not in item STM tasks. Nevertheless, it would have been interesting to investigate item and order STM in the native language of BL speakers and to compare their native (L1) and second language (L2) processing. Future research should look into this further. Also, it needs to be considered that there might be a disadvantage in memory processing in a second language (see e.g., Chincotta, Hyönä, & Underwood, 1997; Durgunoglu & Roediger III, 1987; Sanchez, et al., 2010; Thorn, et al., 2002). However, only correctly recalled trials were analysed and behavioural results did not reflect this concern. In fact, BL speakers were more accurate in item STM than ML speakers and no other differences between groups were found.

Taken together, the hypothesis was confirmed with ML and BL adults showing different patterns for neuroelectric activity only in the order STM task but not the item STM task. ML participants showed higher amplitudes in order STM in the LPC time window (500-700ms post stimuli) in frontal left and parietal right regions[11] compared to BL participants.

7. Study 3: Monolingual Children

Like in ML adults, differences between item and order STM processing have been demonstrated in ML children in a number of behavioural studies (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Mosse & Jarrold, 2007; also see Section 6.1. in Chapter 1 in this thesis). Importantly, like in ML adults (see Majerus, Poncelet, Elsen, et al., 2006), order STM, but not item STM, predicted vocabulary development in 4 to 5 year old monolingual French-speaking kindergarten children (Leclercq & Majerus, 2010). Majerus, Poncelet, Greffe et al. (2006) found that in 4-year-olds and 6-year-olds only order STM and not item STM was significantly related to vocabulary development but in 5-year-olds only item STM and not order STM was significantly related to vocabulary development. Majerus, Poncelet, Greffe, et al. (2006) proposed that memory for serial order and memory for item identity follow different developmental trajectories in their relationship with monolingual vocabulary acquisition. So far, no neuroimaging studies on STM have been conducted with children.

However, as ML children show comparable results in behavioural studies to ML adults, similar differences are expected in patterns of neuroelectric activity for item and order STM processing: Order STM is expected to show larger P300 and larger LPC compared to item STM tasks.

[11] Note that LPC in frontal regions might reflect feature encoding while LPC in posterior regions might reflect recollective processes. However, to interpret this result further source localization would be needed to investigate the appropriate source of where the ERP waveforms originated.

It has been suggested that item and order STM show different developmental trajectories in monolingual children (Majerus, Poncelet, Greffe, et al., 2006; also see Section 6.1. in Chapter 1 for a review). By comparing the neural processing of item and order STM in ML children and ML adults we aim to track down possible developmental changes in the event-related EEG signal. We know that item STM reflects knowledge of phonological, orthographic and semantic properties. As investigated by recent studies (see e.g. Gathercole & Baddeley, 2011 and Garlock, Walley, & Metsala, 2001) ML children are less experienced in language than ML adults (i.e. show less knowledge of phonological, orthographic and semantic properties of a given language) differences are expected in patterns of neuroelectric activity for item STM.

As no previous STM studies using ERPs have be conducted with ML children it is difficult to predict developmental changes in neural processing of item and order STM. However, some previous studies with adults could give insights into possible changes in the event-related EEG signal in item STM between ML children and adults: As described before (see Section 3 in this chapter), several researchers have identified P200s using principal components factor analysis which have been shown to be positively related to retrieval in short-term memory experiments (e.g., Chapman, et al., 1981; Friedman, et al., 1981; Taylor, et al., 1990). Evidence suggests that P200 amplitude may be related to partial retrieval of semantic information from long-term memory into working memory (e.g., Barnea & Breznitz, 1998; Wlotko & Federmeier, 2007) as it appears to be related to subsequent recognition (Smith, 1993) or recall in short-term memory. ML children are expected to show greater P200 amplitude compared to ML adults as they are likely to exhibit higher involvement of language-related sub-processes when activating item STM. In another study Nittono et al. (1999) found that the P300 increased as task demands increased and suggested that P300 might reflect individual differences in working memory capacity (for more details see Section 5.3. this chapter). From this finding ML children are expected to show greater P300 amplitude compared to ML adults, as the item STM task might make greater demands on working memory capacity in ML children compared to ML adults. As described before (see

Section 6 this chapter), it has been suggested that enhanced LPC might indicate a stronger involvement of language-related sub-processes which might affect the retrieval of item STM (Alvarez & Holcomb, 1999). From this finding ML children can be expected to show greater LPC amplitude compared to ML adults as they are likely to feature higher involvement of language-related sub-processes when activating item STM.

7.1. Participants

16 children (7 male), right handed, were recruited via the Sussex University community and friends. Age ranged from 9 to 11 years with a mean age of 9.9 years (SD=0.9 years). Nine additional participants had to be excluded due to excessive artefacts following technical problems during recording or excessive movement artefacts.

This age group was selected for several reasons:

1) As children's brain waves change when they enter puberty children not older than 11 were selected (see Cycowicz, 2001 for a review of memory developmental changes in ERPs in children);
2) They were able to read well and sit still for longer than 30 minutes;
3) They were comparable to monolingual and bilingual children from whom behavioural data had been collected (see Chapter 4 in this thesis).

Parents completed a questionnaire for each child to ensure they did not suffer from any neurological impairments (e.g. epilepsy, metal implants) or from any skin allergies, take medication for depression, have dyslexia or any other learning disabilities, have a cold or flu or were getting over a cold or flu at the time they intend to participate nor had suffered severe head injury in their lifetime (i.e. loss of consciousness for more than 30 minutes).

Ethical Considerations: Written informed consent (for details see Appendix A5) was given by every parent/guardian and it was made clear that they had the right to withdraw at any time. Both, parents and children, were thoroughly introduced to the laboratory and its equipment (e.g. EGI net, Faraday cage) before the experiment. As this was the first study with children in this laboratory, the premises were made child-friendly (i.e. glowing stars in the Faraday cage, blankets and pillows for comfort). In addition, the instructions to the item and order STM tasks were rephrased in a more child friendly way (see Appendix A6 for details)

Like in the previous studies in this chapter, prior to statistical analysis data were screened and found to be normally distributed. After careful visual inspection, selected outliers were removed (see Krauledat, Dornhege, Blankertz and Müller, 2007, for details on rendering EEG data more robust by removing outliers).

All subjects were paid for participation. The study was approved by the Ethics Committee of the School of Life Sciences of the University of Sussex.

7.2. Results

7.2.1. Analysis I: Item and Order Processing in ML Children

7.2.1.1. Behavioural Results

Monolingual children were more accurate in the order than the item recognition task (t(15)=3.34, p=.004): In the item task, they achieved an accuracy of 65% (Std.=11.81), in the order task 74% (Std.=13.67). The average reaction time (RT) in the item task was 2527ms (Std.=335ms), in the order STM task 2488ms (Std.=264ms). No statistical differences in the reaction times of item and order tasks were found. See Figure 24 for details.

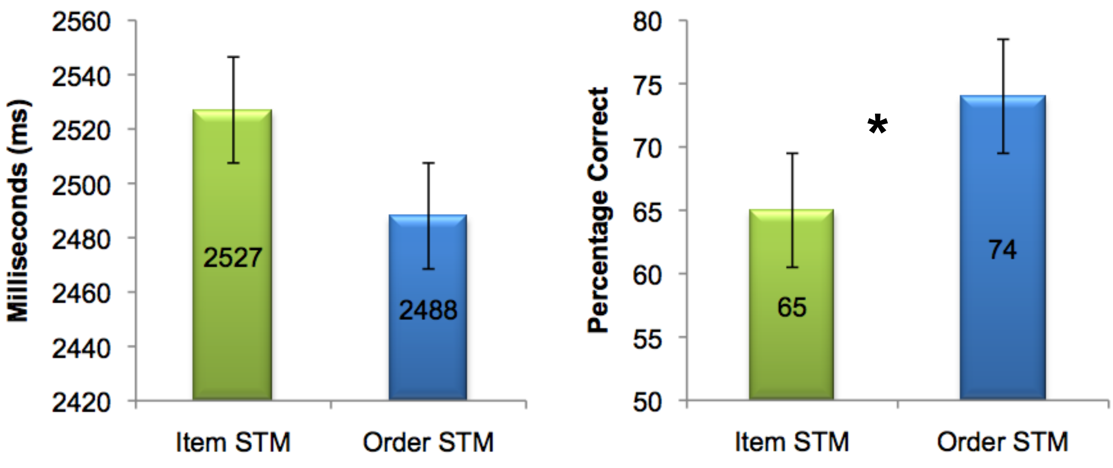


Figure 24: Reaction time (milliseconds) and accuracy (percentage correct) in item and order STM tasks in ML children (*=p<.05)

7.2.1.2. Event Related Potentials

7.2.1.2.1. Visual Analysis of ERPs

The ERP grand mean waveforms for item and order verbal STM for monolingual children are plotted in Figure 25. Figure 26 contain voltage maps computed by subtracting ERPs for item and order STM tasks. They were included to better visualize the scalp distribution of verbal STM effects at the three time points P200, P300 and LPC.

As can be seen in these figures, the monolingual children show a clear P200 in the left frontal electrodes F3 and Fz for both item and order STM. Order seems to elicit a stronger P200, similar to monolingual adults. In the voltage map (item STM ERPs subtracted from order verbal STM ERPs) these differences do appear both frontally and occipitally as can be seen by the strong positivity elicited by the difference waves.

The P300 is also elicited in parietal regions (P3, Pz), for both item and order verbal STM. Here, the voltage map shows no strong differences for item and order, but the ERP data in the graph indicate numerically greater positivity in order, compared to item STM tasks.

LPC can be found in parietal areas and shows higher positivity in the item STM task compared to the order STM task. However, order STM tasks elicit stronger positivity in frontal and central areas. In the voltage map, these differences are reflected by negativity (order less positive than item) in parietal regions, compared to some positivity in frontal regions (order more positive than item).

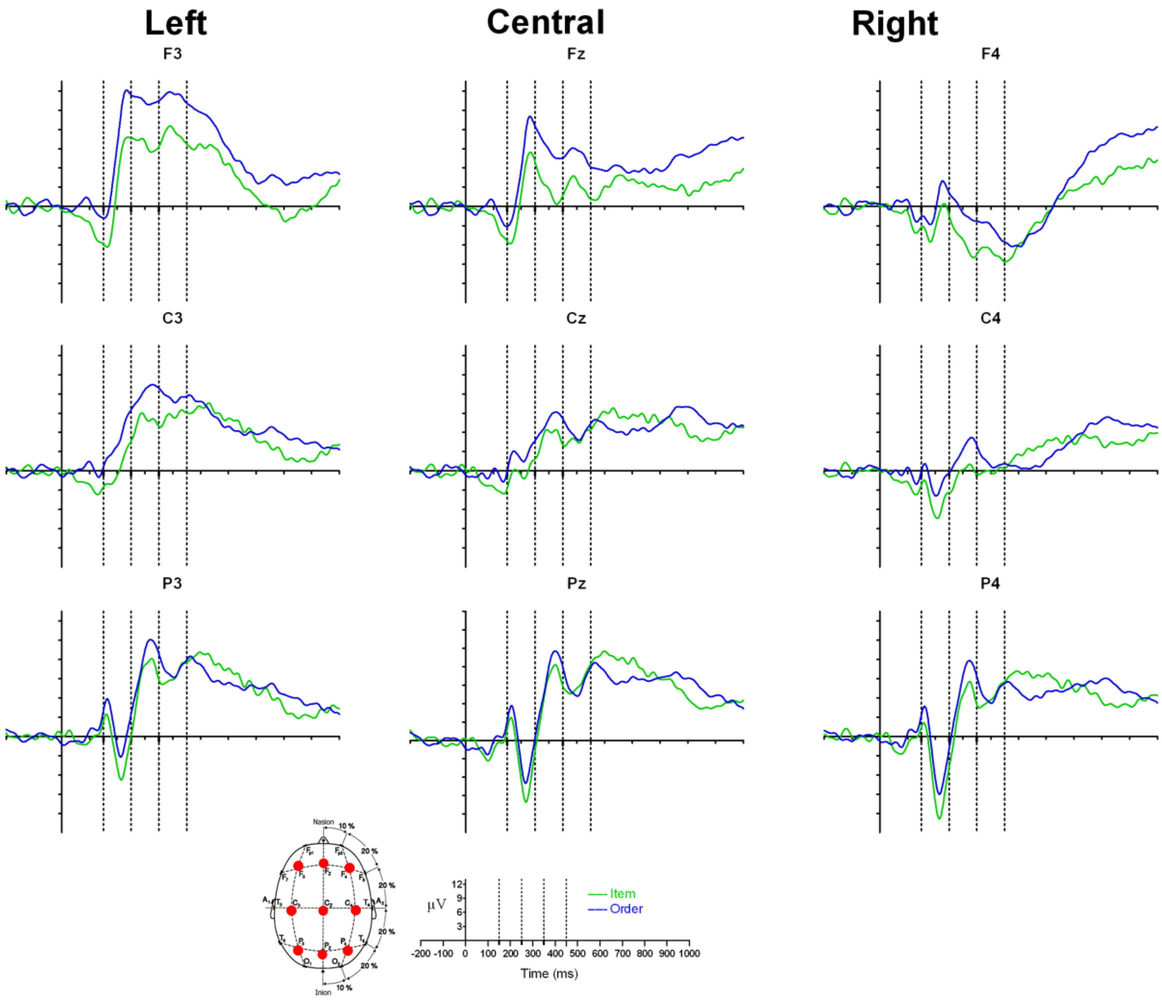


Figure 25: Waveforms for item and order STM in ML children

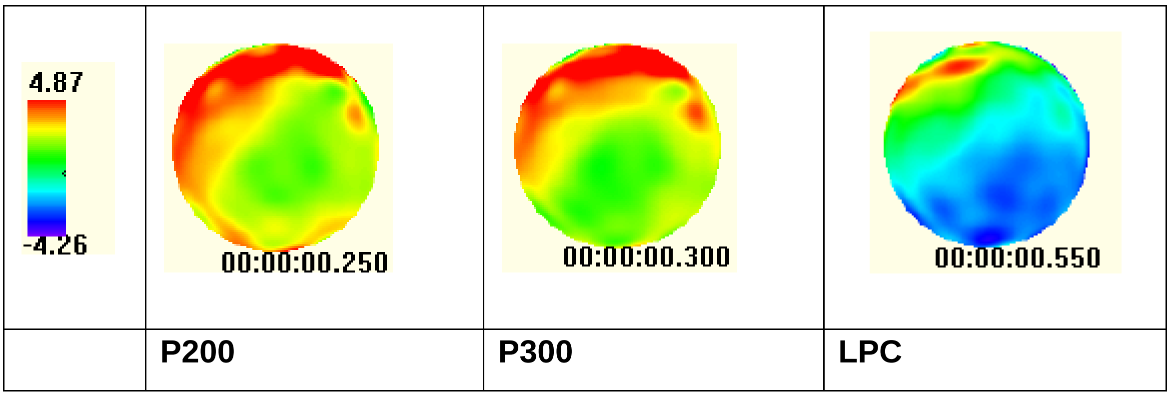


Figure 26: Voltage maps computed by subtracting ERPs for item and order STM tasks for the three time points in ML children.

7.2.1.2.2. Analysis of ERP Data

Analysis was carried out on the same principles as for the monolingual and bilingual adults.

P200 data. A marginal interaction of task by location was found 200 to 300ms post stimuli in mean amplitude, F(1,15)=3.479, p=.082, with order showing more frontal positivity than item and less of a difference compared to item in parietal areas (see Figure 27 for details).

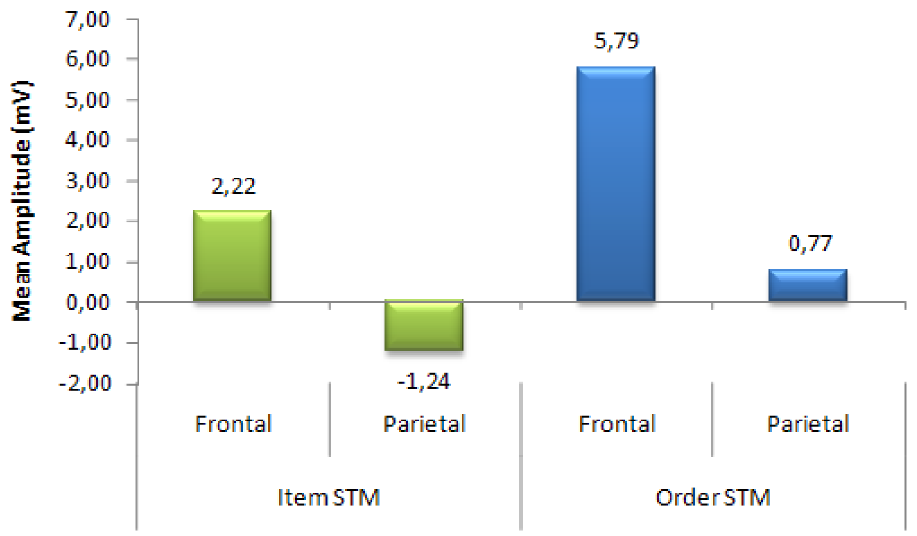


Figure 27: Task by Location mean amplitude effect at P200 in ML children

P300 data. A significant interaction of task by location was found 250 to 350ms post stimuli in mean amplitude, F(1,15)=6.812, p=.020, with order showing more positivity in both frontal and parietal areas than item which showed less positivity in frontal parts of the skull compared to parietal areas (see Figure 28 for details).

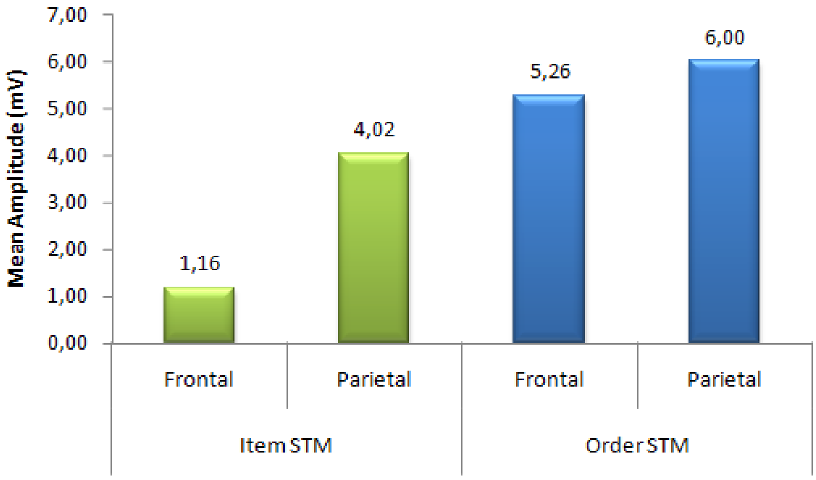


Figure 28: Task by Location amplitude effect at P300 in ML children

LPC data. A significant interaction of task by hemisphere, F(1,15)=4.630, p=.048, as well as a task by location effect, F(1,15)=10.048, p=.006, was found 500 to 700ms post stimuli when looking at mean amplitude. Also, the 3-way interaction task by hemisphere by location was significant with F(1,15)=6.957, p=.019. In frontal regions, order elicited more positivity compared to item STM, but both item and order STM elicited more positivity in the left hemisphere. In parietal regions, item elicited more positivity compared to order STM, see Figure 29 for details.

Figure 29: Task by Hemisphere by Location amplitude effect at LPC in ML children

7.3. Interim Discussion

Before interpreting the children´s results further, it needs to be considered that the immature brain of children is subject to developmental changes in information processing. Compared to a mature adult brain, the immature brain shows differences in electrophysiological responses to incoming stimuli, which may be related to either cognitive growth[12] or brain maturation[13] (Ridderinkhof & van der Stelt, 2000). Not enough publications are available to date to base the interpretation of results on previous children´s EEG data hence

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[12] Cognitive growth is reflected by changes in thinking, typically described as being increasingly efficient, creative, or complex; cognitive growth may be promoted by major life events (such as entry into kindergarten or school) or by brain growth (such as the development of the frontal lobe) or, perhaps, by interaction of nature and nurture (Bold, 1999).

[13] Human brain maturation is a complex, lifelong process that involves changes in neuron formations in the brain (see e.g., Toga, Thompson, & Sowell, 2006).

the interpretation of findings is based on what we know from findings in ML adults (see Section 5.2. this chapter).

The hypothesis that order STM would elicit higher amplitudes compared to item STM in the P300 and LPC time windows was partially confirmed. A marginal significantly difference in order and item STM emerged in the P200 component with order STM eliciting more positivity compared to item STM in left frontal regions. The difference in order and item STM amplitude became significant in the P300 time window. In the LPC time window order STM elicited more positivity compared to item STM over frontal electrodes. However, in parietal regions item STM elicited more positivity compared to order STM.

A number of studies suggest that P200 is related to retrieval processes in STM (Chapman, McCrary, & Chapman, 1978; Friedman, Vaughn, & Erlenmeyer-Kimling, 1981; Taylor, Smith, & Iron, 1990) and it has also been found to be more positive in ML adults compared to BL adults in order STM tasks in frontal regions. Hence it could also be argued, that order STM required more demanding retrieval processes compared to item STM in ML children. One possible explanation is that they might rely more on the lexical phonological network when performing verbal STM tasks similarly to ML adults (see Section 5 this Chapter or also Adam & Collins, 1978; B. R. Dunn, et al., 1998). Note that it has been argued before that the P200 component might reflect an early P300 (see e.g., B. R. Dunn, et al., 1998).

As predicted, the difference in order and item amplitude became significant in the P300 time window. Children showed similar results to ML adults, which leads to the conclusion that P300 differences seem to be stable over time, independent of developmental changes in monolingual speakers. Therefore, like in ML adults it can also be argued for ML children, that order STM compared to item STM demanded more short-term memory capacity (for previous research supporting this claim see also Blumhardt, 1996; Donchin, 1981; Fabiani, et al., 1986; L. Howard & Polich, 1985; Key, et al., 2004; Nittono, et al., 1999; Pelosi, 1998; Pelosi, et al., 1992; Polich, 2007; Starr & Barrett, 1987). As argued before with ML adults, the difference in P300 could also be an outcome of different memory strategies that participants used in order STM compared to item STM tasks. However, in both tasks, they had to remember four items which were presented sequentially and hence memory strategies were intended to be similar across tasks. An additional question that would arise is why BL adults did not show these differences if they were established purely through different memory techniques.

For the LPC the hypothesis was only partially confirmed. A significant interaction of task by location was found in LPC, where order STM elicited more positivity compared to item STM in frontal regions. However, in parietal regions item STM elicited more positivity compared to order STM. In ML adults it has been argued that LPC processes occurring in the frontal cortex, particularly the prefrontal cortex, might index feature encoding, whereas parietal LPCs index reconstructive or recollective processes (Smith, 1993). Note that as mentioned before (see Section 8.2.1. in Chapter 1) it is difficult to relate the scalp location of ERPs to underlying brain processes without using source localization methods. Care is especially needed when interpreting results from children based on findings in adults, again as pointed out above. Generally speaking, LPC has been found to be larger in bigger memory sets and with slower reaction times, suggesting that its presence might reflect subjective difficulty in performing a task (Pelosi et al., 1992). However, no reaction time differences were found in ML children between item and order STM tasks and in fact, they performed better in order STM tasks which make subjective difficulty in performing a task unlikely.

As argued for ML adults, LPC might also index relatively simple lexical or semantic encoding especially when found in frontal brain regions (Besson, et al., 1992; B. R. Dunn, et al., 1998; Paller & Kutas, 1992; Paller, et al., 1995; Smith, 1993; Van Petten, et al., 1991) but this argument becomes irrelevant as our task was designed to control for word frequency, lexicality and semantics (i.e., word type).

The most plausible explanation for differences in LPC is that ERPs in this time window may rather index reconstructive or recollective processes reflecting more elaborative processes based on information stored in long-term memory. This might take up more neural activation in order STM compared to item STM (similar to ML adults). As pointed out when discussing the results for the ML adults, recent findings in a longitudinal study with children (see Chapter 4) showed that ML English speaking children outperformed BL German/English children in item STM but BL German/English children outperformed ML children in order STM. This finding suggests that ML children (and our data also suggest ML adults) draw more on the lexical phonological network when performing verbal STM tasks than the order STM tasks. This could explain the additional involvement of neural activation in order verbal STM tasks.

It would be interesting to conduct a longitudinal developmental study with ERP-examination before children learn a second language, and after they have learned a second language to see if this might impact on item/order STM processing. Again to anticipate some results of Chapter 4, Section 3, in ML children learning French it was found that exposure to a second language had a strong impact on item STM, i.e. children showed similar results in English (L1) and French (L2) item STM after only a short time of exposure to the second language. However, serial order STM was correlated with the item STM measures, indicating that the two components of phonological STM, while functionally distinct, are related (see Chapter 4, Section 4). As the children in our EEG experiment were all before puberty (i.e. the brain still shows greater flexibility and, for example, young children can still learn a second language without accents compared to older children or adults), this might be reflected in an interaction of task and location in their ERP data.

7.3.1. Analysis II: Comparison of Monolingual Children and Monolingual Adults

Both ML adults and children only speak one language (compared to bilinguals who show a broader lexical phonological network as they possess two different pools of vocabulary). Given that order STM is estimated to reflect a richer lexical phonological network involved in learning a second language, it is expected to activate more similar patterns for neuroelectric activity in both ML adults and children, as both groups only speak one language and hence their lexical knowledge is assumed to be more similar. However, subtle differences might occur as order STM is related to language learning capacity which might be more evolved in ML adults compared to children due to the larger vocabulary pool that ML adults have acquired over time. If differences in order occur, they are expected to be reflected in higher mean amplitudes in the LPC component. This hypothesis is based on previous findings with BLs showing larger positivity in order STM compared to ML adults (see Section 6.2. this chapter). BL adults compared to ML adults possess a richer lexical phonological network while ML adults as opposed to ML children feature a larger vocabulary pool.

Taken together, higher amplitudes in P200, P300 and LPC are expected in item STM in ML children compared to ML adults. For order STM no significant differences between adults and children are expected.

7.3.2. Behavioural Results

Two-way repeated measures ANOVA (2x2) with memory task (item versus order) as within subject variable and group (children versus adults) as between subject variables showed a main effect of task on accuracy, $F(1,35)=22.848$, $p<.001$. Both ML adults and children achieved overall higher accuracy in order STM tasks (mean=80 percentage correct, SE=.017) compared to item STM tasks (mean=73 percentage correct, SE=.017). No interaction with group was found.

For reaction times, a marginal task by group effect was found, $F(1,35)=3.486$, $p=.07$, with adults showing overall faster reaction times compared to children but adults showing faster reaction times in item STM tasks compared to order (item mean=1576ms, SE=61ms, order mean=1664ms, SE=56ms) while children performing faster in order STM tasks compared to item (item mean=2527ms, SE=66ms; order mean=2477, SE=61ms). See Figure 30 for details.

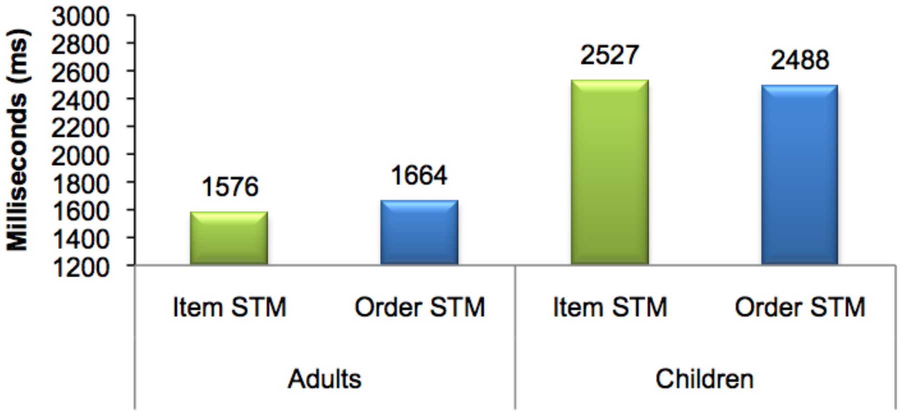

Figure 30: Marginal Group by Task effect in behavioural comparison of ML adults and children

7.3.3. Event Related Potentials

7.3.3.1. Visual Analysis of ERPs

The ERP grand mean waveforms for item and order verbal STM for monolingual adults and children are plotted in Figure 31. When comparing the waveforms, it can be seen that children elicit much higher mean amplitude for item and order STM in the P200 in the left frontal electrode. The P300 also seems to be a lot more pronounced in ML children compared to adults. Also, it peaks a little bit earlier than in ML adults, where the peak is only distinct in order STM, while item STM shows overall positivity without a real peak. As before, the mean amplitude is set at a much higher level in ML children compared to adults. Differences can be found in the LPC time window, where in parietal areas order STM elicited higher positivity in ML adults, while item STM elicited higher positivity in ML children. In frontal and central areas, order STM showed stronger positivity in both ML adults and children with children showing higher amplitude levels than adults.

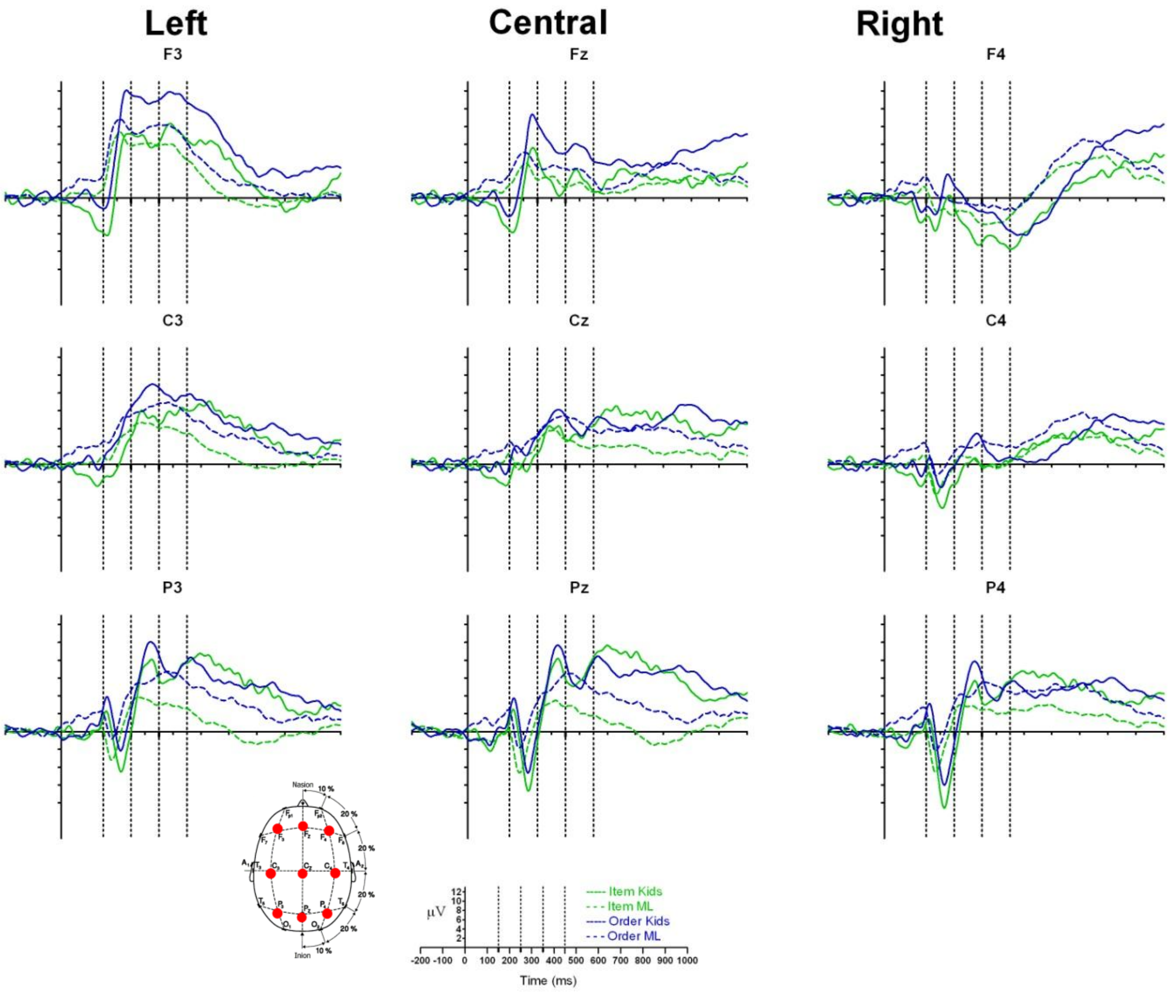

Figure 31: Waveforms for item and order STM in ML adults and ML children

7.3.3.2. Analysis of ERP Data

Data were analysed in a similar manner to those from ML adults and BL adults.

P200 data. A significant group by task by location effect was found 200 to 300ms post stimuli, F(1,34)=4.600, p=.039 (for details see Figure 32). In the item STM task, adults and children both showed higher amplitudes in frontal compared to parietal electrode sites. Compared to adults, children elicited both higher amplitudes in frontal regions and lower amplitudes in parietal regions in the item and the order STM task. Overall item STM elicited more positivity in both children and adults compared to order STM.

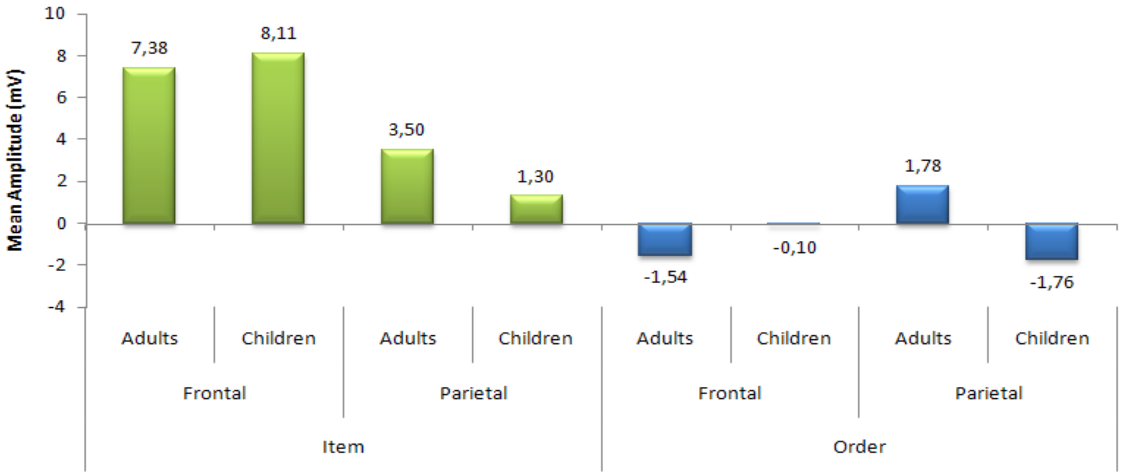

Figure 32: Group by Task by Location amplitude effect at P200 when comparing ML children and adults

To investigate which cortical areas showed the biggest group differences in amplitude in item and order STM tasks, a post-hoc two-way ANOVA with a mixed (2x8) design, with group (adults or children) as a between subjects variable and task location (Item STM Front Left, Item STM Front Right, Item STM Parietal Left, Item STM Parietal Right, Order STM Front Left, Order STM Front Right, Order STM Parietal Left, and Order STM Parietal Right) as a within subjects variable was conducted. The analysis revealed significant differences in mean amplitude 150 to 250ms post stimuli in item STM in left frontal sites only, $F(1,34)=6.163$, $p=.018$. ML children showed a significant lower mean amplitude (mean: 1.43, SD: 6.48) compared to ML adults (mean: 5.72, SD: 3.80). No differences were found in order STM amplitude level.

P300 data. A significant group by task by location effect was found 300 to 400ms post stimuli, $F(1,34)=8.747$, $p=.006$ (for details see Figure 33). For item STM children elicited less positivity in frontal regions and more positivity in parietal regions compared to adults. Order STM showed higher mean amplitudes in children compared to adults in both frontal and parietal regions.

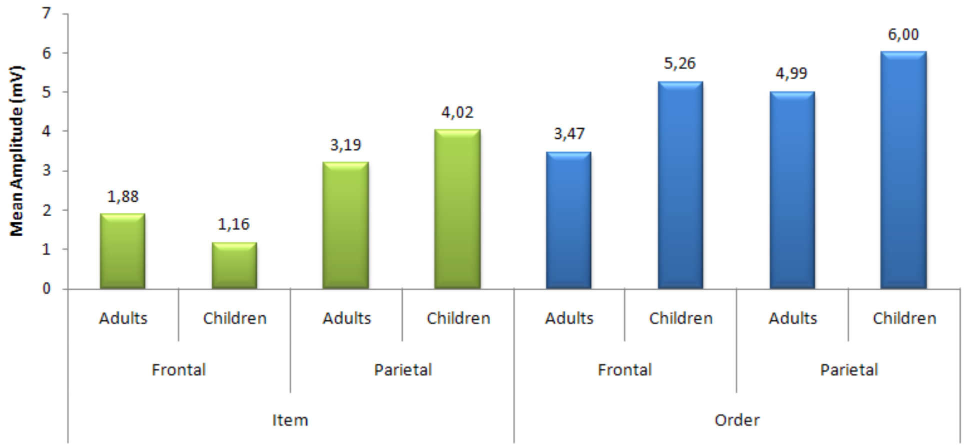

Figure 33: Group by Task by Location amplitude effect at P300 when comparing ML children and adults

Post-hoc two-way ANOVA revealed no significant differences in mean amplitude in either item STM or order STM.

LPC data. A significant task by location by group effect was found for amplitude differences in the LPC time window, 500 to 700ms post stimuli, $F(1,34)=19.290$, $p<.001$, see Figure 34 for details. For item STM, children revealed higher positivity than adults in frontal regions and less positivity in parietal regions. In the order STM task children showed more positive amplitudes than adults in both frontal and parietal regions.

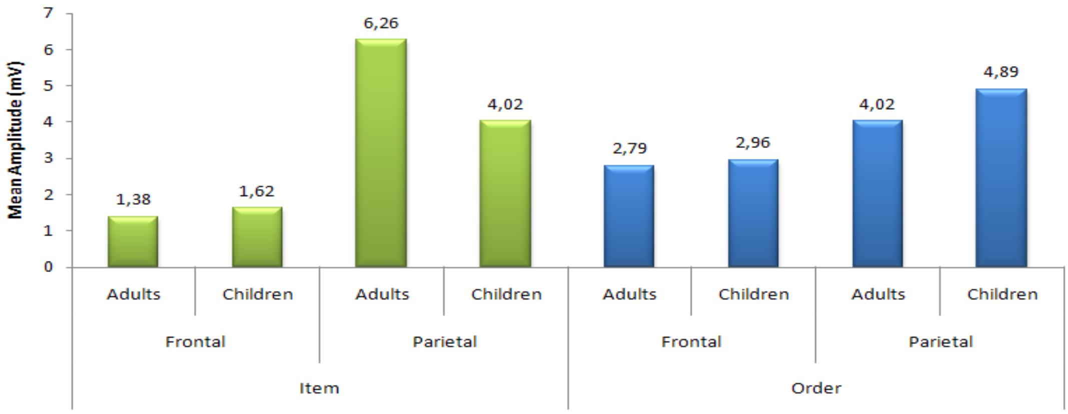

Figure 34: Group by Task by Location amplitude effect at LPC when comparing ML children and adults

Post-hoc two-way ANOVA revealed significant differences in item STM in parietal left, $F(1,34)=16.885$, $p<.001$, and right regions, $F(1, 34)=6.654$, $p=.014$, see Table 3 for details. ML children showed higher mean amplitudes compared to ML adults. No significant differences for order STM were found.

		Mean	SD
Item Parietal Left	ML adults	0,15	4,73
	ML children	6,73	4,84
Item Parietal Right	ML adults	2,06	3,55
	ML children	5,79	5,11

Table 3: Differences in ML adults and children in item STM amplitude 500 to 700ms post stimuli

7.3.4. Interim Discussion

To investigate developmental changes in item and order STM further, we compared monolingual children's data to monolingual adult's brain waves. It is important to note that children might lack pre-existing representations in their long-term lexical or semantic memories (see e.g., Cycowicz, Friedman, Snodgrass, & Duff, 2001) making it more difficult for them to memorize those items. This difference is also reflected in behavioural data as children show significantly lower accuracy rates than adults indicating the task overall was more difficult for them. Hence, when it comes to interpreting the comparison of ML adults and ML children, the developmental aspect needs to be strongly considered, because the immature brain of children is subject to developmental changes in information processing (Chourchesne, 1978; Gomarus, Althaus, Wijers, & Minderaa, 2006; Polich, Ladish, & Burns, 1990; Yordanova & Kolev, 1997). Cycowicz et al. (2001) talk about "continuing maturation of the brain networks assessing novelty or familiarity" and Friedman, de Chastelaine, Nessler and Malcom (2010) point out that while familiarity appears to mature relatively early in development and is maintained with aging, recollection shows protracted development and deteriorates with aging[14].

The hypothesis was largely confirmed: Item STM showed significant higher amplitudes compared to order STM. However, differences were also found in order STM eliciting higher positivity in ML children compared to adults in LPC - this difference was not significant in post-hoc analysis. The results suggest that order STM is processed similarly in ML adults and children while item STM shows age specific components:

[14] Cycowicz et al. (2001) looked at 7 to 8 year old children and college students and the authors Friedman et al. (2010) investigated 9-10 year old children, 13-14 year old adolescents, 20-30 year old young adults and 65-85 year old older adults using ERP and behavioural data.

In the P200 component, children showed significantly lower amplitude in item STM compared to adults[15]. A group by task by location interaction was found in P300, with children showing lower item STM amplitude in frontal regions and higher amplitude in parietal regions. Post-hoc analysis comparing group specific waveforms of tasks in defined regions did not reveal any differences. In LPC, children revealed higher mean amplitudes in item STM in parietal regions.

The P200 differences are likely to simply reflect the lack of pre-existing representations in long-term lexical or semantic memories in children (Cycowicz, et al., 2001) making it necessary for children to use more neural network power to perform the task with similar results to adults.

A strong P300 was elicited in both ML adults and children with ML children showing overall more positivity in both item and order STM tasks compared to ML adults. One interpretation of these findings is that the differences occur due to task difficulty, as pointed out by Pelosi et al. (1992). However even though adults were faster in item and order STM tasks no main effect of group was found for either accuracy or reaction time. Nittono et al. (1999) argued that higher P300 amplitude might reflect individual differences in working memory capacity and concluded that the P300 increased as task demands increased. Children showed higher positivity in parietal regions compared to adults in item STM tasks. Hence it can also be claimed that both the item and order task might have demanded additional processes in ML children compared to ML adults, or ML children might simply use their working memory resources less efficiently than compared to adults. A related possibility is that children use more complex memory strategies than adults, even though they had the same instructions (Otten & Donchin, 2000).

During LPC, ML children showed more positive amplitudes for item STM compared to ML adults. No differences in the order tasks were found. As argued before, LPC has been found to be larger in greater memory sets and

[15] Note that this difference is unfortunately not reflected in Figure 31 as it only depicts waveforms of chosen electrodes while statistics was performed on groups of electrodes.

slower reaction times suggesting that its presence might reflect subjective difficulty in performing a task (Pelosi et al., 1992). However, no main effect of group was found in the behavioural data. Importantly, LPC has also been found to index more elaborative processes based on information stored in long-term memory (see also Besson, et al., 1992; Paller & Kutas, 1992; Van Petten, et al., 1991; Van Petten & Senkfor, 1996). It is more likely that the LPC reflects more elaborative processes which need to be activated during item STM tasks in children compared to adults as reflected in higher frontal amplitude rates during item STM.

Czernochowski, Mecklinger, Johansson and Brinkmann (2005) suggest that children rely predominantly on recollection during recognition judgments, even in the absence of efficient memory control processes. The latter processes enable adults to monitor and verify the retrieved information and to control non-target retrieval in the service of adequate source memory performance. Czernochowski et al. (2005) add to the discussion, and argue that children rely primarily on recollection to make their recognition-memory decisions, whereas young adults employ familiarity and recollection flexibly. Similar results were found by Yordanova and Kolev (1997), who looked at 6 to 10 year old children and adults and found a late parietal P400–700 which manifested significantly larger amplitudes for oddball targets than for non-targets. This component decreased with age. Yordanova et al. (1997) assume this may reflect a developmental speeding in the processes of stimulus evaluation (see also Kutas et al., 1977) or timing of attentional processes when working memory is updated (see also Polich, 1993). However, Yordanova et al. (1997) also argue that according to criteria of topography, task sensitivity, and changes with development, P400–700 (which is a similar time window as the LPC component in this study) in children could be identified as the P3b. As our data show a rather distinct P3 in children that is much larger compared to adults, it is unlikely that the LPC component in this study can be identified as P3b in children. In fact, the children in this sample do show a second positive peak at about 450-500ms that is highly likely to reflect LPC.

Taken together the hypothesis was largely confirmed: Item STM revealed several age related differences which are likely to reflect children´s lack of pre-existing representations in their long-term lexical or semantic memory, inefficient use of the same memory processes or use of different memory processes. English ML children and adults seem to process order STM more similarly than item STM. However, marginal amplitude differences in the P300 component indicate that in children both item and order STM might have demanded additional processes compared to adults.

8. Discussion

This chapter comprised three studies investigating differences in patterns of neuroelectric activity in three groups of participants: Monolingual adults, bilingual adults and monolingual children. Monolingual adults served as a base for the evaluation of possible differences in item and order processing. Bilingual adults were included to explore possible differences in patterns for neuroelectric activity in item and order STM due to language learning capacities. Monolingual children were included to examine potential developmental changes in the event-related EEG signal.

To test the hypothesis that verbal item and order STM involve different neural mechanisms, a novel task differentiating item and order verbal STM was administered using time-sensitive ERP measures. Study 1 investigated neural processes underlying item and order STM in ML adults. As hypothesized, monolingual adults generated larger P300 and LPC amplitudes in order compared to item STM tasks. Importantly, order STM showed (marginally) more positive amplitude compared to item STM in the right parietal part of the brain, an area previously discussed as the location of serial order processing (see e.g., Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006; for an EEG study supporting this finding see Turconi, et al., 2004). This could point further to a right parietal location for serial order STM processing (see also the next chapter with a study using TMS for a detailed discussion). The finding in the P300 component indicates that in MLs order memory involves more context updating compared to item memory or in other words, it could be argued, that order STM demanded more working memory capacity in ML speakers compared to item STM (see e.g., Nittono, et al., 1999). In the LPC component, order STM elicited overall higher positivity in parietal areas compared to the item STM task. The difference might reflect subjective difficulty in performing a task (Pelosi et al., 1992). Indeed, ML adults were significantly slower in order STM tasks compared to item STM tasks (but more accurate). It was suggested that in ML speakers the order STM task might possibly need additional cognitive resources. In addition it has been suggested that enhanced LPC might indicate a stronger involvement of language-related sub-processes which might affect the retrieval of items from STM (Alvarez & Holcomb, 1999). One interpretation of this finding is that ML adults might draw more on the lexical phonological network (i.e. item STM) when performing verbal STM tasks, rather than drawing from order STM directly (see also Section 7 this chapter with ML English speaking children for a similar argument).

Study 2 examined item and order STM processing in BL adults. Similar patterns of neuroelectric activity in item and order STM to those found in ML adults were expected. However, the hypothesis was not confirmed. The only differences in the neuro-electrical correlates for item and order STM were found in LPC. Here, order STM elicited less positive amplitude compared to item STM in frontal regions. It was argued that (contrary to ML adults) in BLs recollective processes might show stronger involvement of language-related sub-processes in item verbal STM compared to order STM due to the processing of the tasks in their second language.

An additional analysis compared cortical waveforms of ML and BL adults. Differences were expected in order STM processing but not item STM processing. This hypothesis was confirmed. This finding indicates that BLs and MLs process item STM similarly but not order STM. Importantly, ML and BL speakers showed (marginally) significant amplitude differences in order STM in the right parietal area, an area previously reported as possible region for the locus of a specific STM store for serial order information (more specifically right IPS, for more details please refer to the next chapter presenting a TMS study). This hence leads to the argument that rather than “BLs recollective processes might show stronger involvement of language-related sub-processes in item verbal STM compared to order STM due to the processing of the tasks in their second language" they simply might not engage in as much cognitive processing as MLs in order STM tasks. When looking back at the analysis of differences in patterns for neuroelectric activity between item and order STM in BLs, it could be suggested that BLs process order STM similarly to item STM tasks, at least in their second language.

In Study 3, ML children´s processing of item and order verbal STM was explored. It was hypothesised that ML children would show similar differences in patterns for neuroelectric activity in item and order as found in ML adults. This hypothesis was largely confirmed. Order STM showed higher mean amplitudes in P300 and LPC compared to item STM. Marginal differences already emerged in the P200 time window with more positivity in order STM compared to item STM. However, contrary to the hypothesis, item STM elicited more positivity compared to order in parietal regions in the LPC time window. It was argued that (similar to the finding in ML adults) order STM required more demanding retrieval processes compared to item STM in ML children. One possible explanation is that ML children might rely more on the lexical phonological network when performing verbal STM tasks (similarly to ML adults see Section 5 this chapter or also Adam & Collins, 1978; B. R. Dunn, et al., 1998). The finding that item STM elicited more positivity compared to order STM in parietal regions was thought to reflect cognitive flexibility in children.

The ERP data of children were then statistically compared to the ERP data from ML adults to investigate developmental trajectories in patterns of neuro-electrical activity. It was hypothesized that item STM would be processed differently in children due to poorer knowledge of phonological, orthographic and semantic properties of vocabulary items compared to ML adults. This hypothesis was largely confirmed. While there was evidence that various ERP measures were similar in order STM in ML adults and ML children, item STM showed age specific changes: Item STM elicited higher mean P200 amplitudes in parietal regions in children compared to adults and elicited higher mean LPC amplitudes across the whole head in children compared to adults. One potential explanation for this effect could be that the P200 differences reflect the lack of pre-existing representations in long-term lexical or semantic memories in children (Cycowicz, et al., 2001). Higher frontal amplitudes during item STM in the LPC time window were thought to reflect additional elaborative processes (as argued by e.g., B. R. Dunn, et al., 1998; Paller & Kutas, 1992; Smith, 1993) which need to be activated during item STM tasks in ML children compared to ML adults. The P300 showed overall higher amplitudes in item STM which might reflect individual differences in working memory capacity as suggested by Nittono et al. (1999). These authors found that the amplitude of the P300 increased as task demands increased. It can hence be claimed that both the item and order task might demand additional processes in ML children compared to ML adults, or ML children might simply use their working memory resources less efficiently than adults. A related possibility is that children use more complex memory strategies than adults, even though they had the same instructions (Otten & Donchin, 2000). Taken together, the differences between ML children and ML adults probably reflect developmental effects of the growing brain such as the lack of pre-existing representations in long-term lexical or semantic memories in children making it necessary to activate additional processes to perform as well on the STM tasks as adults.

In order to further investigate whether the differences in ML speakers are a general finding or rather language specific, the study of ML speakers should be repeated with a group of ML speakers with a different native language, e.g. German. Compared to English, German is a more flexible language in terms of sentence structure and word order and hence that fact alone could change participants' processing of item and order verbal STM.

For bilingual participants it would be interesting to test bilingual adults in both languages, their native language (L1) and second language (L2). This would make comparisons easier as a within-participant design instead of a between-participant design could be used, and hence many problems of interpreting the data such as different language levels (i.e. monolinguals vs. bilinguals) or cognitive levels (i.e. children vs. adults) can be overcome. The question would be whether similar results would be obtained for both languages. If they were, this finding would strengthen the claim that in BL speakers, item and order STM differences are indeed differences in verbal STM processing, independent of what languages they speak. The BL participants in the study above were mainly German native speakers, even though all of them spoke English in a highly proficient way and used it on a day-to-day basis and as pointed out above, German is a more flexible language in terms of word order in the language compared to English. Then again the question whether similar results would be obtained dependent on a given language or dependent on the fact of “being bilingual” alone (independent of which languages are mastered) could also be investigated by including a BL group of native English speakers conducting the task in English and comparing them to our current group of BL native German speakers (or speakers of another foreign native language). If both groups show similar results it would suggest that the findings arise because the participants are bilingual rather than because of any specific properties of the language(s) they speak (i.e. German being more flexible in its sentence structure). However, in the current study German native speakers were chosen as it was very hard to find a group of homogenous native English BL speakers all learning the same language and speaking it at a similar high proficiency level.

Including a group of low proficient bilingual adults could be helpful for further insights – the question would be if low proficient BL adults show a more similar profile to ML adults compared to high proficient BL adults as they might be more similar to monolingual speakers in their STM processing of verbal material. For this study the group of BL speakers could consist of English participants learning a second language to make them comparable to the ML English group.

It would have been interesting to include a group of bilingual children to directly compare item and order STM processing in these two developmental groups. Furthermore the adult BL group and child BL group could have also been compared. However, it was impossible to find enough bilingual children (let alone German/English bilingual children) to take part in this study. Another interesting question in the future will be to see if the neural underpinnings of item and order STM change over time as children learn a second language (i.e. in a longitudinal study). However, one complication here could be the fast maturation of children´s brains over puberty if testing older children, and the problem of getting younger children to sit still long enough to perform the tasks

Taken together, the present experiments provide some evidence for differences in patterns for neuroelectric activity underlying item and order STM in ML adults, BL adults, and ML children. The findings in this chapter support recent models of verbal STM that distinguish between item and order components (e.g., Botvinick & Plaut, 2006; Brown, et al., 1999; Burgess & Hitch, 1999; Gupta, 1996; Majerus, 2008). They also are in line with recent fMRI studies that found different patterns of activation during item and order STM tasks in French ML and English-French BL speakers (Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006).

Chapter 3: Investigation of the Role of the Left and Right Intraparietal Sulcus during Item and Order Verbal STM Activation

1. Introduction

As discussed in detail in Section 2 in Chapter 1 verbal STM is strongly related to vocabulary knowledge (see e.g., Gathercole, et al., 1999; Gathercole, et al., 1992; Gupta, 2003). However, the precise nature of the relationship remains unclear. Recent studies suggest that at least two separate processes operate in verbal STM: short-term memory for serial order and for item information (see e.g., Henson, Hartley, et al., 2003; Poirier & Saint-Aubin, 1996; see Chapter 1, Section 4 onwards for a literature review). Evidence that these two processes may involve different neural mechanisms has been provided by fMRI studies (see Chapter 1, Section 8.2 for a review) and the EEG studies reported in Chapter 2.

Functional magnetic resonance imaging (fMRI) studies have identified a number of brain areas activated by both item and order STM, and some that are uniquely activated only by one or the other. One of the most consistently activated regions during all verbal STM tasks is the intraparietal sulcus (IPS, see e.g., Awh, et al., 1996; Marshuetz, et al., 2000; Paulesu, Frith, & Frackowiak, 1993), more specifically the left anterior IPS (Majerus, Poncelet, Van der Linden, et al., 2006). However, its precise role remains a matter of debate. While some authors consider the IPS to be a specific store for serial order information (e.g., Linden, et al., 2003; Turconi, et al., 2004), other data suggest that it may serve a more general function – that of attentional focalization (e.g., Becker, MacAndrew, & Fiez, 1999; Ravizza, et al., 2004).

Majerus et al. (2006) investigated these two hypotheses in an fMRI experiment by presenting participants with two different verbal STM conditions – one that probed recognition for word identity and one that probed for word order. The analysis assessed the functional connectivity of the left IPS with distant brain areas. The authors assumed that if the IPS has a role of attentional focalization, then it should be involved in both order and item conditions, but it should be connected to different brain regions, depending on different types of information (order versus phonological/orthographic information) that need to be remembered in STM. Their results showed that the left IPS was activated in both order and item STM conditions but for different reasons: during *order STM*, the left IPS was functionally connected to serial/temporal order processing areas in the right IPS, premotor and cerebellar cortices, whereas during *item STM* tasks, the left IPS was connected to areas in the superior temporal and fusiform gyri associated with phonological and orthographic processing. The authors pointed out that like Marshuetz et al. (2000) and Henson et al. (2000), they systematically obtained greater activation in the right IPS for the order STM condition and hence concluded that the right IPS might thus be a good candidate region for the locus of a specific STM store for serial order information.

In addition, results with ML speakers in the previous chapter using EEG also revealed marginal differences between item and order STM in the right parietal area. This pattern of activation has also been previously shown in an ERP study by Turconi et al. (2004) who found that order judgments for number pairs elicited higher evoked potentials in right parietal areas, relative to left parietal areas. Other neuroimaging data on time processing and episodic memory also have implicated the right IPS in retrieval of temporal order (Cabeza, Anderson, Houle, Mangels, & Nyberg, 2000; Rao, Mayer, & Harrington, 2001).

Another fMRI study using a different design to further investigate the role of IPS in item and order STM was conducted in 2007 by Majerus, Bastin, Poncelet, Van der Linden, Salmon et al.. The authors used a face STM paradigm, in which participants were asked to remember either the order, or identity of faces. The regions activated in the order encoding task were identical to those activated in the order condition of the verbal STM task in the Majerus et al. (2006) study. However, during identity encoding, the left IPS showed preferential functional connectivity with right temporal, inferior parietal and medial frontal areas – brain regions that typically activated in other tasks involving detailed face processing (Haxby, et al., 2000; Henson, Goshen-

Gottstein, et al., 2003; Kanwisher, et al., 1997; Platek, et al., 2006; Postle, Druzgal, & D'Esposito, 2003; Sugiura, et al., 2000). The authors concluded that these results further support an attentional account of left IPS involvement in visual STM and further highlight the importance of the left IPS as an attentional modulator in a variety of STM tasks.

A key point to be noted is that fMRI studies can only demonstrate an association between a cortical area and task performance. A method that can provide a way of potentially establishing causality is Transcranial Magnetic Stimulation (TMS). As briefly described in Chapter 1, Section 8.2.2., TMS can be used to explore the importance of regions of interest in the brain by artificially disrupting neurons in this region in healthy participants and investigating the impact of this disruption on behavioural data, i.e. reaction times or accuracy (for more details refer to Section 2, this chapter).

On the basis of the recently obtained fMRI data described above, it was predicted that TMS over the left IPS should affect order and item STM in equal ways while right IPS stimulation should only affect order STM in monolingual English speaking adults. A further rationale for stimulating the IPS in the present study is that it lies within the parietal cortex, very close to BA40 (the inferior parietal lobule which lies below the horizontal portion of the intraparietal sulcus) a known key region of the phonological loop (see e.g., Henson, et al., 2000; Lauro, Reis, Cohen, Cecchetto, & Papagno, 2010; Paulesu, et al., 1993; Romero, Walsh, & Papagno, 2006; Vallar & Papagno, 2002; studies will be described in more details in Section 3 in this chapter).

Taken together, in the current study, the aim was to further investigate the role of IPS in order and item verbal STM in monolingual English speakers and to determine whether it has a causal role during verbal STM tasks by using transcranial magnetic stimulation (TMS).

2. Transcranial Magnetic Stimulation

TMS involves the discharge of a painless transient electro-magnetic field through the skull, causing trans-synaptic depolarization of cortical neurons. This is achieved by holding a magnetic coil close to the head in a constant position. Participants place their head in a chin-rest and the coil is fixed with a frame in the correct location. The coil releases a single magnetic pulse (or series of magnetic pulses) which generates an electromagnetic field that induces depolarization of neurons via induction of an electromagnetic current in the brain. TMS can be used to disturb, excite, or inhibit the activity in a given brain area. Its spatial resolution is highly dependent upon the shape of the stimulating coil but can be on the order of a few millimetres with certain coil types (e.g. figure eight coils with 45 m circular diameter components can be as precise as localising an individual finger representation on the primary motor cortex, see Ro, Cheifet, Ingle, Shoup, & Rafal, 1999). Figure of eight coils are most commonly used when attempting to influence relatively small areas of cortex (1-2 cm sq) as a focal point of stimulation is produced at the intersection of the two circular components.

The temporal resolution of TMS is variable and dependent upon the stimulation parameters used. Researchers typically employ one of the following protocols: Single pulse TMS, paired pulse TMS, and high frequency or low frequency repetitive (r) TMS. Single pulse temporal resolution is very high and can provide information about brain function of the order of milliseconds. It provides one single TMS pulse, causing underlying neurons to depolarize and discharge an action potential. The effects are very short lived and hence this method is used in so called online settings, i.e. the pulses are delivered during the performance of a specific task, for example synchronized with trial onset, in order to interfere with the targeted cognitive processes. Paired pulse TMS is similar to single-pulse TMS but uses two single pulses in very short succession. It has the same effects as single pulse TMS but the temporal effect on neurons is longer than in single pulse TMS stimulation. High frequency repetitive TMS (rTMS) usually refers to stimulus rate of more than 1 Hz (Rossi, Hallett, Rossini, & Pascual-Leone, 2009) and is supposed to have mainly excitatory effects on neurons. Mechanisms are thought to reflect changes in synaptic efficacy akin to long-term potentials (LTP) and long-term depression (LTD); see Fitzgerald, Fountain, and Daskalakis, 2006. Like single- and double-pulse TMS, high frequency rTMS is used in online settings, i.e. during the performance of a specific task.

Low frequency rTMS is usually associated with pulse rates of 1Hz or less (Rossi, et al., 2009) and has mainly an inhibitory effect (Hoffman & Cavus, 2002). Low frequency rTMS has been found to reduce the excitability of the neurons underlying the stimulated area for a short period of time after the stimulation has stopped. Compared to high frequency rTMS, the effects in low-frequency rTMS are subtle, lasting about half the time of the TMS stimulation (i.e., six minutes low-frequency rTMS stimulation affects underlying neurons for about three minutes: see Thut & Pascual-Leone, 2010). Low-frequency rTMS is typically given as a prolonged continuous stimulation in an offline setting, i.e. before the performance of a specific task. Effects are only revealed as very small changes in sensitive performance measures such as reaction times. For a review of TMS see Walsh and Pascual-Leone (2005) or recent review papers (e.g., Guse, Falkai, & Wobrock, 2010; McKinley, Bridges, Walters, & Nelson, 2012; e.g., Nollet, Van Ham, Deprez, & Vanderstraeten, 2003)

Low- and high-frequency rTMS bear quite different safety risks in view of their different effects on motor excitability. High frequency rTMS has been known to induce seizures at high stimulus intensities and rates. This method will not be used in this study. Like single-pulse or paired-pulse TMS, low-frequency rTMS can be employed both in volunteers and patients with neurological diseases without risks (Tassinari, Cincotta, Zaccara, & Michelucci, 2003). Low frequency rTMS reduces cortical excitability, and as such is currently being investigated as a potential treatment for epilepsy (Tassinari et al, 2003). Low frequency rTMS is widely used as a therapeutic intervention in depression and other psychiatric and neurological disorders, with patients typically receiving 10-15 daily sessions in which 600-1000 pulses are administered over 10-15 minutes. There have been no incidences of TMS induced seizure reported using low-frequency rTMS or single pulse TMS in either therapeutic settings with patient participants or research settings with healthy volunteers. For a list of strength and weaknesses of the TMS method in research please refer to Appendix B2.

Altogether, TMS is a very useful technique for researchers interested in determining the role different brain areas play in controlling language. Low frequency rTMS is especially useful as it provides a window of disruption that is sufficiently long to investigate the cognitive processes underlying item and order STM.

3. TMS Studies on Verbal STM

So far, no study has investigated the IPS involvement in verbal STM using TMS. Indeed, very few studies have looked at the effect of transcranial magnetic stimulation over the intraparietal sulcus (IPS) on any aspect of cognitive function. Of those that have, most are investigations into the role of the IPS in perceptual processes and are not relevant to the topic of this thesis. There are, however, a small number of studies that are potentially relevant. For example, Dormal, Andres and Pesenti (2008) used TMS to investigate differences between numerosity and duration processing in the left IPS. This study might be of interest as serial order information is numerical as stimuli (words/letters/numbers) are remembered in a certain position, so an overlap is plausible (as suggested by Marshuetz, et al., 2000; see Section 1.4.2.2.1. in Chapter 1 for more details). In the TMS study by Dormal et al. (2008), participants had to compare the numerosity of flashed dot sequences or the duration of single dot displays before and after 15 min of 1 Hz rTMS over one of three sites (left or right IPS, or the vertex chosen as a control site). Compared to the control site, performance was only slowed down for the numerosity comparison task after left IPS stimulation, whereas it was not affected for the duration comparison task for any of the parietal sites. The authors conclude that the parietal area is critically involved in numerosity processing (but is not involved in duration processing). They point out that their results reveal at least one cerebral site where duration and numerosity comparison processes dissociate. This study highlights the possible importance of left IPS for serial order information (but cannot provide information about item STM).

Whilst there are no studies that have used TMS to investigate the role of IPS in verbal STM, there are several studies that have explored the STM processes by stimulating other cortical regions. In 1996, Düzel, Hufnagel, Helmstaedter and Elger used TMS on 20 patients with temporal lobe epilepsy (six with left temporal lobe epilepsy, ten with right temporal lobe epilepsy and four with bi-temporal epilepsy). The authors wanted to investigate whether TMS can help to achieve a non-invasive individual localization of verbal and non-verbal memory functions during preoperative epilepsy by inducing focal, material-specific memory deficits. Verbal STM was measured by Digit Span performance and non-verbal STM was measured by Corsi Block performance. Single TMS pulses were timed synchronously or 200 ms post-stimulus onset over the left and right temporal cortex and vertex while participants had to remember sequences of items from the verbal and non-verbal memory tests presented on a computer. No significant differences in the number of errors on the verbal and non-verbal memory span were found but significant changes to serial position effects were found in patients with Left Temporal Epilepsy. Only in this group did TMS over the left temporal lobe induced significantly better performance on recency items in the verbal Digit Span test while TMS over the vertex significantly increased errors on items in the recency position - in the group with right temporal lobe epilepsy no such effects were observed. Düzel et al. suggests that the results indicate that in the presence of left temporal lobe stimulation, TMS can induce qualitative material specific changes in verbal memory (he also refers to this as the phonological loop). Düzel further implies that the dissociation of TMS effects for temporal and vertex stimulation imply that TMS can selectively influence specific phonological loop components and that the phonological loop has a functionally and neuro-anatomically multi-modular structure.

More recently, Mull and Seyal (2001) explored whether transient functional disruption of the dorsolateral prefrontal cortex (DLPFC) would impair performance in 9 subjects on a serial letter working memory task. In the task, 33 letters were displayed serially and subjects were required to state if the letter just presented was the same as the letter presented three positions back. Between letter presentations, single-pulse TMS was applied in blocks to the left and right DLPFC. Increased errors were found when TMS was applied over left DLPFC relative to the no TMS control condition, while TMS over the right DLPFC did not alter working memory performance. The authors suggest that their results indicate that the left prefrontal cortex has a crucial role in at least one type of working memory.

Mottaghy, Gangitano, Krause and Pascual-Leone (2003) used TMS to explore the chronometry of parietal and prefrontal activations in verbal working memory. Six healthy volunteers were asked to perform a two-back verbal working memory task with the first four letters of the alphabet, while the left or right inferior parietal (which lies below the horizontal portion of the intraparietal sulcus) and prefrontal cortex was stimulated at 10 different time points 140-500ms between the presentation of the letters. It was found that interference with task accuracy was induced by TMS earlier in the parietal cortex than in the prefrontal cortex and earlier over the right than the left hemisphere. The authors suggest a propagation of information flow from parietal to anterior cortical sites converging in the left prefrontal cortex during verbal STM tasks. Their results also suggest that activation flows primarily from right to left.

In a review paper Mottaghy (2006) points out that there are at least two possible explanations for bilateral involvement of dlPFC and PPC in verbal working memory: He refers back to the idea of a complex neuronal memory network and notes that after the visual input, the information might be processed bilaterally in parallel, evolving from posterior to anterior and finally converging within the left dlPFC.

Lauro, Reis, Cohen, Cecchetto and Papagno (2010) used TMS to investigate the involvement of the phonological loop in sentence comprehension. They tested the behavioural consequences of TMS over BA40 (the inferior parietal lobule which lies below the horizontal portion of the intraparietal sulcus) and BA44 (Broca's area), known key regions of the phonological loop (for a review see Henson, et al., 2000; Paulesu, et al., 1993; Romero, et al., 2006;

Vallar & Papagno, 2002), on language comprehension, using low frequency 1Hz rTMS. 12 right handed monolingual English speaking participants were assessed for their level of comprehension by means of two tasks: a sentence-to-picture matching task, with sentences varying in length and syntactic complexity and a sentence verification task. 30 minutes of low frequency rTMS over the left inferior parietal lobe (BA40) significantly reduced accuracy for syntactically complex sentences and long, syntactically simpler sentences, while rTMS over Broca´s area significantly reduced accuracy only for syntactically complex sentences. Most importantly for this thesis, rTMS applied over the left but not right inferior parietal lobe also impaired performance on sentences in which word order was crucial. The authors suggest that neural correlates of the phonological loop (left BA40 and BA44) are both involved in the comprehension of syntactically complex sentences while only left BA40 (inferior parietal lobe), corresponding to the short-term memory store, is recruited for the comprehension of long but syntactically simple sentences.

As mentioned before, a key point to be noted is that fMRI studies can only demonstrate an association between a cortical area and task performance. If one can demonstrate by stimulating a specific region that performance on a task is impaired, then this provides powerful support for the argument that that brain area is required for efficient task performance. The aim of the present study is to determine whether, as predicted by Majerus et al. (2006), impairing the left IPS using TMS will influence both order and item verbal STM compared to impairing a control-site. However, impairment of the right IPS should only show effects in the order STM tasks.

4. Methods

4.1. Participants

Twenty-four healthy, monolingual English speaking participants (11 male/13 female; mean age: 22.30 years) took part in this study. They all passed the following inclusion criteria: Medically fit, healthy, and not currently receiving psychoactive medication, able to provide informed consent, and right handed. They did not show current or previous psychiatric or neurological illness, metal implants, cardiac pacemaker, history of epilepsy or fits, migraine, any history of brain damage (or surgery), neurological disorders, current treatment with any psychoactive medication, and pregnancy. A TMS Screening Questionnaire (adapted from Keel, Smith, & Wassermann, 1999) and a revised version of the Edinburgh Handedness Inventory (adapted from Oldfield, 1971) were completed by each participant. Participants with a previously taken structural magnetic resonance imaging (MRI) scan signed a consent form allowing the researchers to use it in the TMS study (see Appendix B1 for consent form and questionnaire).

4.2. Materials

For the first ten participants a T1-weighted MRI was obtained (TR 11.4 ms, TE 4.4 ms, flip angle 15°, 192 0.9 mm-slices, no gap) on a 1.5 Tesla Siemens Avanto scanner with a standard head matrix coil. These pictures were then transformed via MATLAB into a format that could be used by MRIcro software for 3D navigation. The images were used to identify the left and right anterior IPS. For this the MINIBIRD magnetic tracking system (Ascension Technologies, Vermont, USA: www.ascension-tech.com), a neuronavigation technique, was used to locate the left and right IPS. For more details see Figure 36.

In the 10 participants for whom the site of TMS stimulation was guided by fMRI images, the IPS region corresponded closely to the P3/P4 location according to a standard 10-20 electrode placement cap.

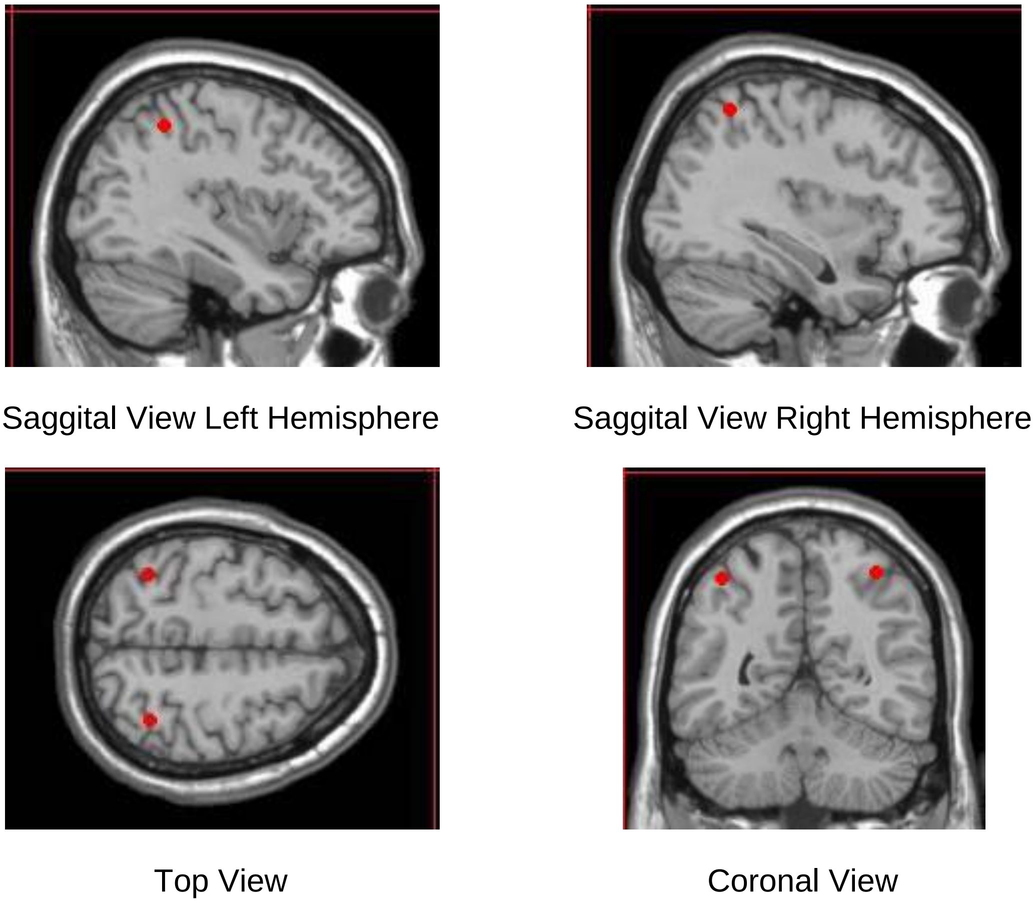

Figure 35: Transcranial magnetic stimulation (TMS) regions of interest – left and right anterior intraparietal sulcus (IPS) – shown for example participant

A number of other studies have also found that P3/P4 closely corresponds to the IPS (e.g., Ashbridge, Walsh, & Cowey, 1997; Chambers & Mattingley, 2005; Dambeck, et al., 2006; Hilgetag, Theoret, & Pascual-Leone, 2001; Mottaghy, Döring, Müller-Gärtner, Töpper, & Krause, 2002; Vesia, Monteon, Sergio, & Crawford, 2006) as identified by a standard 10-20 electrode placement cap. For the remaining 14 participants, fMRI scans were not available, so the standard 10-20 electrode placement cap was used to identify the IPC area for stimulation[16].

As a control condition, also called "sham condition", the vertex was chosen. In this area the coil was turned over, so that the participant experienced the same sensation as with TMS but without stimulation to an area.

Stimulation intensity was set at a fixed level of 60% of maximum stimulator output. A 6 min (360s) train of pulses was applied at 1Hz. The TMS-coil was navigated over the stimulation site with the handle pointing down, and the coils placed tangentially to the skull. It was held in position during stimulation with a customized coil-holder. TMS was applied using a MagstimSuperRapid stimulator (Magstim, Withland, UK) and a 70mm figure-of-eight coil, which can induce a maximum magnetic field of 2.2 Tesla at the scalp site, rTMS was applied either over the left anterior IPS, the right anterior IPS or a sham site (vertex). Each site was stimulated on a separate day and the order of stimulation was randomised across participants. Participants watched a short movie during blocks of rTMS stimulation and then performed the task immediately after. All participants were tested in a quiet, dimly lit room with their head stabilised with a chin- and forehead rest during the rTMS phase. Reaction time (RT) and accuracy (A) were recorded using responses via mouse click.

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[16] The 10-20 system is an internationally recognized method to apply and describe the location of electrodes used in electroencephalography experiments. It ensures standardized reproducibility. The system is based on the relationship between the location of a specific electrode and the underlying area of the cerebral cortex. The numbers 10 and 20 refer to the fact that the actual distances between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. In P3/4, the letter P stands for Parietal respectively. The numbers 3 and 4 refer to the electrode positions (even number on right hemisphere, odd number on left hemisphere).

4.3. Experimental Design

Each participant attended three separate sessions. In each session TMS was applied to a different cortical location (left IPC, right IPC, sham). Each session lasted 60 -90 minutes. Within each session, two tasks where administered: An order short term memory task and an item short term memory task.

rTMS was applied in an offline condition, 6 minutes prior to every block; every block lasted approximately 2 minutes. In every session participants were stimulated on one site (site randomized across participants) and performed alternating item and order STM tasks. As explained in Section 2 in this chapter, low frequency rTMS affects behaviour for approximately half as long as the stimulation lasts. Hence the design we used allowed us to investigate the influence of left and right IPS on item and order STM. See Figure 37 for details.

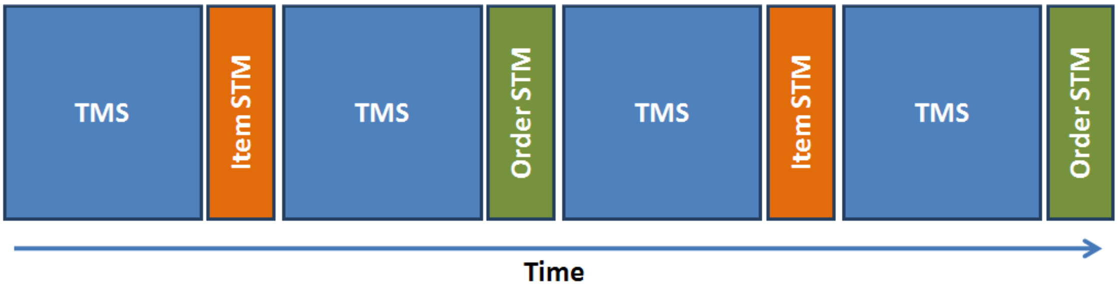

Figure 36: Procedure of TMS session

4.4. Experimental Procedure

In both tasks, four words appeared successively in the centre of the screen, followed by a four second pause. Then, two probe words appeared. In the order STM condition, participants had to judge whether the order of the probe words was the same as their order in the first four words that were shown. In the item STM task participants had to judge whether the two probe words had appeared before or not. The probe items remained on screen until participants responded. See Figure 38 for details.

The task was constructed similarly to the task in the EEG experiment reported in Chapter 2 (see 4.2.1.) except that the two probe words appeared for as long as the participant needed to respond. This was changed as it was expected that TMS would slow down participants' reaction times but not their accuracy rates. In the order STM task, the probe trials always contained two words that were adjacent in the study phase, but they were presented either in the same or the reversed order in the test phase. By probing adjacent but not distant positions, we were able to maximize the difficulty and sensitivity of the order STM condition as very precise order representations are needed when remembering two adjacent items. The task was to decide if the words had been presented in the same order (press YES button) or not (press NO button). Half of the trials were presented in the same order and half were not.

In the item identity STM task either both probe words had been presented in the study phase or one had not been presented in the study phase but instead a word that differed in only one sound from the original word in the study phase (e.g.. manure instead of mature) was shown. The use of negative probes (i.e. the presentation of one member of the minimal pair in the study list and the other member in the probe array) was designed to increase the difficulty of the item STM condition because words differed only minimally from the target word. Participants had to judge whether the two probe words were identical to any of the words in the study list (press YES button if they were identical, NO button if they were not identical). Participants completed a total of 6 blocks, 3 blocks with the item STM tasks and 3 blocks with the order STM tasks per session (i.e.left IPS, right IPS stimulation or vertex). When participants started with an item STM block, they continued with an order STM block and vice versa, until they had completed all 6 blocks. Each block consisted of 25 trials and there were a total of 75 trials per condition per session. For more details of instructions and examples for the item and order STM tasks see Appendix A4 and for details on stimuli refer to Appendix A8.

The task was programmed using E-prime 2.0 (Psychology Software Tools Inc., Pittsburgh, PA). Each of the four words appeared for 1000ms with a pause of 250ms (with a blank screen) between words. The four words were followed by a four second retention interval (blank screen shown).

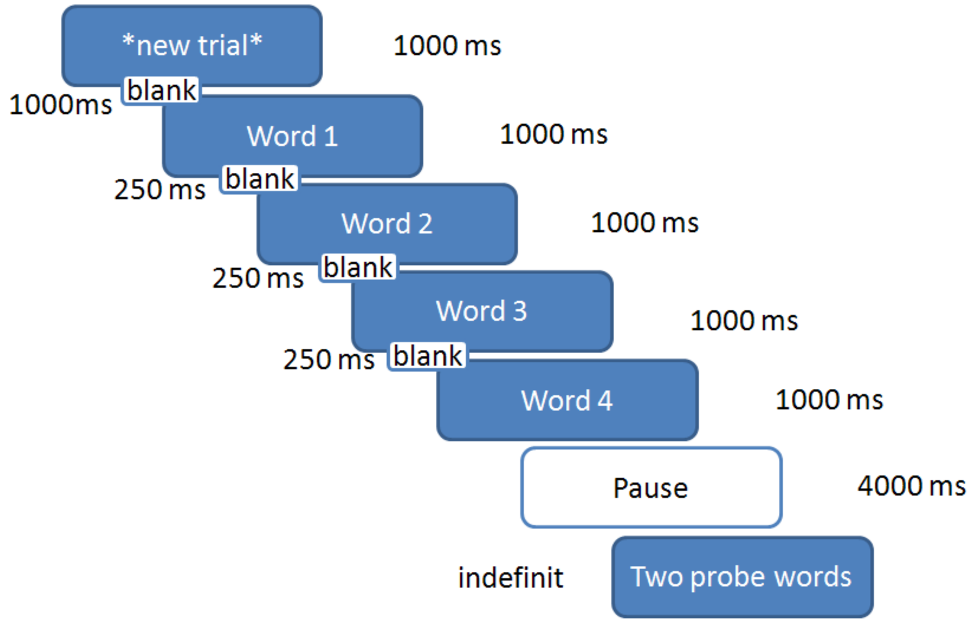

Figure 37: Study design

Participants did a short off-line practice session of 5 trials before each session to make sure they understood the task. They were paid 25 GBP for participating.

5. Results

To avoid extreme latencies having undue influence on the participant means, all trials in which latencies were two standard deviations (STD) above or below each participant's mean were removed prior to averaging across the tasks and conditions.

Response accuracy and reaction time as a function of condition (right IPS, left IPS and sham) are shown in Figures 39 and 40.

The effects of TMS on item and order STM performance were explored with repeated measures ANOVA with the factors TMS location (left TMS, right TMS, Sham) and task (item, order). A main effect of task was found for reaction times – participants were faster at item STM compared to order STM (F(1,23)=19.74, p<.01). This difference was expected due to the recruitment of serial order scanning processes which take time (see also Majerus, Poncelet, Van der Linden, et al., 2006 or Section 5.2.1., Chapter 2). Importantly there was no main effect of TMS location and no interaction between TMS location and task. See Figure 39 for details.

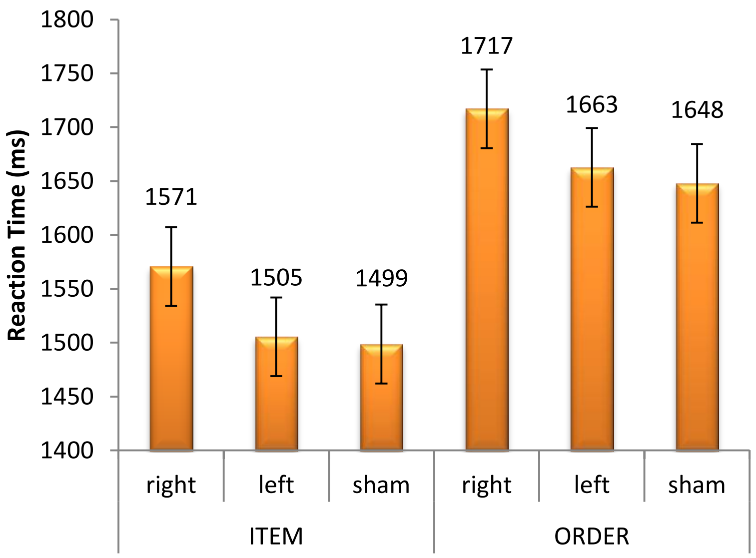

Figure 38: Mean reaction time in ms for item and order tasks for all three TMS locations

When looking at accuracy scores, a strong trend towards a main effect of task (F(1,23)=3.78, p=.06) was found. There was also a trend towards a main effect of TMS location (F(2,46)=3.06, p=.06) but no interaction between TMS location and task (F(2,46)=.249, p>.1). See Figure 40 for details. In order to explore the main effect of TMS location, errors were collapsed over item and order tasks, and paired t-tests revealed that there was a trend for participants to make more errors after TMS stimulation over the left IPS (t(23)=1.98, p=.06) compared to sham but not right IPS (t(23)=1.40, p>.1). See Figure 40 for details.

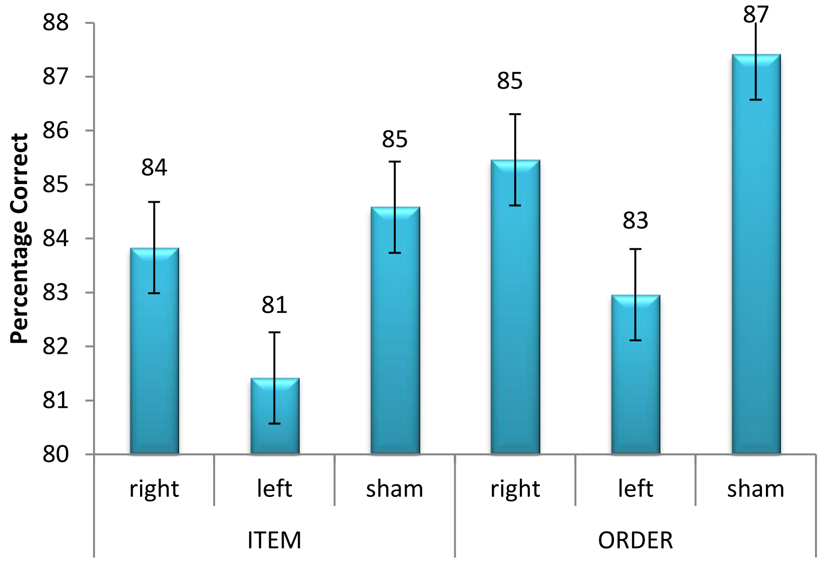

Figure 39: Mean accuracy (correct percentage) for item and order task for all three TMS locations

6. Discussion

Majerus, Poncelet, Van der Linden, et al. (2006) argued that the left IPS was activated in both memory for serial order and item identity tasks but for different reasons: during order STM, the left IPS was functionally connected to serial/temporal order processing areas in the right IPS, premotor and cerebellar cortices, while during item STM, the left IPS was connected to phonological and orthographic processing areas in the superior temporal and fusiform gyri. On the basis of these data, it was predicted that rTMS over the left IPS should affect order and item STM equally, while right IPS stimulation should only affect order STM in monolingual adults. The first hypothesis was supported to the extent that TMS over the left IPS resulted in an increase in errors on both item and order tasks (although it did not impact on latency). However, there was no support for the suggestion that the right IPS is specifically involved in order STM.

Majerus et al., (2006) suggested that the left IPS acts as an “attentional modulator” of distant neural networks. Support for this position was found in a follow up study by Majerus, Bastin, et al. in 2007 where the authors used different stimuli than before (faces instead of words). Regions activated in the order encoding task were identical to those activated in the order condition of the verbal STM task in the Majerus et al. (2006) study, but during identity encoding, the left IPS showed preferential functional connectivity with right temporal, inferior parietal and medial frontal areas – brain regions that are typically activated in other tasks involving detailed face processing (Haxby, et al., 2000; Henson, Goshen-Gottstein, et al., 2003; Kanwisher, et al., 1997; Platek, et al., 2006; Postle, et al., 2003; Sugiura, et al., 2000). The authors highlight the importance of the left IPS as an attentional modulator in a variety of STM tasks involving words (verbal STM tasks) and faces (visual STM task) as well as item and order STM components.

Our results can confirm the involvement of the left IPS in both item and order STM tasks. However, it is interesting that TMS over the right IPS had no significant specific effect on order STM. There are several potential reasons why we failed to observe such an effect – including a failure to stimulate the precise IPS. Localisation in TMS research is often subject of considerable debate. In the present study, for a subset of participants we used structural scans combined with the MINIBIRD magnetic tracking system, a neuronavigation technique, to identify precisely the left and right anterior IPS. Whilst we were able to confirm previous research in showing that in these participants the IPS was located very close to P3/4 in the standard 10-20 system, individual differences in cortical anatomy mean that it is possible that in our remaining participants we were not always stimulating the precise right IPS. Given the relatively small size of the IPS, future research in this area should consider adopting neuronavigation techniques for all participants. Some researchers have even used mathematical models to co-register a series of neural land-marks using the MRIcro and MiniBIRD coordinates to ensure precision of disruption to regions of interest. This method allows comparison of the position of the MiniBIRD on the scalp relative to the underlying cortical surface with more precision. Another possibility is to use a very sophisticated stereotactic localization system such as Brainsight (Rogue-Research Inc., Montreal, Canada).

Even though the right IPS was found to be an important area for order STM processing in recent fMRI studies (see Linden, et al., 2003; Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, D'Argembeau, et al., 2009; Majerus, Poncelet, Van der Linden, et al., 2006), it must be acknowledged that results of the current TMS study could also suggest that the right IPS might not have a causal role in order STM after all. Other regions may also be worthy of future study. One of the possible regions that might be worth investigating more regarding order STM is the left dorsolateral prefrontal cortex (DLPFC). Henson et al. (2000) were the first to suggest that this region was involved in the processing of temporal order STM. The authors used fMRI to investigate recoding, storage, rehearsal and grouping in verbal STM. They tried to localise processes involved in verbal STM for sequences of visual stimuli (letters and symbols). A network of left-lateralised areas was found, including posterior temporal regions, supramarginal gyri, Broca’s area and dorsolateral premotor cortex. Their findings were consistent with the representation of verbal item information in left posterior temporal areas and short-term storage of phonological information in left supramarginal gyrus. Their findings also suggested that the left dorsolateral premotor cortex was involved in the maintenance of temporal order, possibly as the location of a timing signal used in the rhythmic organisation of rehearsal, whereas Broca’s area supports the articulatory processes required for phonological recoding of visual stimuli. Hence, rTMS applied to the regions of interest in the frontal lobe may be a way to better understand processes that differentiate memory for serial order and memory for item identity. It should be noted however that rTMS applied to the DLPFC is not a straightforward procedure as it can involve some discomfort for participants.

As STM for serial order information, compared to STM for item information, has been shown to be a more critical determinant of language learning capacity and is activated differently in mono- and bilingual speakers it would be interesting to compare the effects of TMS over left and right IPS in mono- and bilingual speakers. Majerus, Belayachi, et al. (2008) showed different activation in high and low proficient French-German bilingual speakers. They found that activation in only the neural networks supporting order short-term memory could differentiate the two groups: During order STM tasks but not item STM tasks, the high proficiency group showed increased activation in the lateral orbito-frontal and the superior frontal gyri. This activation was assumed to reflect the updating and grouped rehearsal of serial order information based on similar findings using fMRI with adult monolingual speakers (Majerus, Poncelet, Van der Linden, et al., 2006). A functional network for order memory involving left IPS, right IPS and right superior cerebellum was found in the high proficiency group, whereas the low proficiency group showed enhanced connectivity in areas involved in item processing namely the left IPS and bilateral superior temporal and temporo-parietal areas. Majerus, Belayachi, et al. (2008) suggest that low proficiency bilinguals activate STM networks for order in a less efficient manner. This relatively strong claim predicts that storage and learning capacity for the order of verbal sequences depends on the left IPS for all participants but may also recruit the right IPS for highly proficient bilingual speakers. A future study therefore could be to see if differences in left and right IPS disruption using TMS can be found in high proficient bilingual speakers compared to low proficient or even monolingual speakers.

The results of the TMS study presented in this chapter provide some support for previous research suggesting that the left IPS is an important cortical region for both item and order verbal STM processes in monolingual English speakers. However, no support was found for the suggestion that the right IPS is a specific store for serial order information.

Chapter 4: Item and Order STM in High Proficient Bilingual Children, Monolingual Children and Children Learning a Second Language

1. Introduction

As described in Section 7 of the general introduction in Chapter 1, several studies have shown that the capacity of verbal short term memory (STM) is related to foreign vocabulary learning in both children and adults (e.g., Masoura & Gathercole, 2005; Service, 1992; Thorn & Gathercole, 1999). However, many questions remain open about the exact nature of this relationship. In the current chapter it is argued that using STM tasks that make a clearer distinction between the different types of information that must be maintained in STM can help to achieve a better understanding of this association (see also Majerus, Poncelet, Elsen, et al., 2006). As reviewed in Chapter 1, Section 4, recent studies suggest a critical division of verbal STM into an item information component and a serial order component. The first two studies in this thesis investigated this issue at a neurological level. It was confirmed that in monolingual (ML) and bilingual (BL) adults as well as ML children, item and order STM activate different neural activity in the brain (see Chapter 2). As pointed out by Majerus et al. (2006), the distinction of item and order STM is fundamental for understanding associations between verbal STM and vocabulary development as they may be differentially related to vocabulary development.

This chapter further investigates item and order STM and their relationship to vocabulary acquisition. To present this complex study more clearly, it has been split into three parts: Part 1 comprises a longitudinal study exploring the relative contributions of item and order STM to vocabulary learning in a group of highly proficient bilingual English-German speaking children and a monolingual German speaking control-group. Part 2 investigates the contribution of item and order STM in second language vocabulary acquisition in a group of English children learning French as a second language. Part 3 investigates differences in performance in item and order STM across these three groups by directly comparing BL English/German children, ML German and ML English children, taking into account findings from Parts 1 and 2. In this study (in all three parts), children aged 7 to 9 years old were studied. This age group was chosen for a number of reasons. Firstly, previous research has not yet investigated this age group. Instead previous research focused on younger children to investigate differences in the relationship of item and order STM on vocabulary learning (see e.g., Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006) as previous research with MLs has suggested that verbal STM might only be a useful predictor in the early stages of vocabulary acquisition, followed by existing vocabulary as more important predictor variable in ML school aged children (see e.g., Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). Secondly testing in a school setting means it is relatively easy to evaluate language learning with a group of children speaking one language at a certain level. Importantly, all verbal tasks were conducted in each of the languages the children speak (i.e. English/German bilingual children did all language tasks and verbal STM tasks in both these languages). This is crucial to explore possible differences in the two languages the children speak (or are starting to acquire) when completing item and order STM tasks. This cannot be investigated in monolingual children who only speak one language.

From the review in Chapter 1 (see Section 4) it is clear that memory for serial order plays an important role in vocabulary acquisition in monolingual children and there is also evidence that this capacity follows a different developmental trajectory to memory for item identity (see Section 2.1.1. in Chapter 1 or for more details Majerus, Poncelet, Elsen, et al., 2006). It has been shown in BL adults that order STM is more strongly related to learning new words than item STM (see Majerus, Poncelet, et al., 2008). In addition to STM capacity, existing vocabulary in a given language is also a strong predictor of vocabulary learning in school-aged children. This has been studied by Masoura and Gathercole (2005) who looked at vocabulary acquisition in 9 to 13 year old bilingual children and showed that in native Greek speaking children with considerable English knowledge, the speed of learning new English words was influenced by existing English vocabulary knowledge but not by phonological STM (measured by nonword repetition, a task that mixes item and order information in verbal STM). This would suggest that at least in bilingual children who have acquired broad and rich networks of phonological representations, existing vocabulary seems to drive further lexical learning and not verbal STM. This would lead to the conclusion that STM might be more important in earlier stages of vocabulary acquisition.

No one has yet investigated the role of item and order STM in vocabulary acquisition in bilingual children and children learning a second language. Doing so can help to uncover the importance of item and order verbal STM in native and second language acquisition. Importantly, in addition to item and order STM, current vocabulary knowledge in the languages spoken by the children are taken into account and its influence on new vocabulary acquisition is compared to the influence of item and order STM.

This study aims to better clarify the role of item and order STM in native language acquisition as well as second language learning to help understand the importance of item and order verbal STM in language acquisition.

2. Part 1: Item and Order STM and Vocabulary Acquisition in Bilingual and Monolingual Children

The key aims of this study were to investigate serial order and item memory capacity in bilingual children, to determine the developmental pathways of these component memory processes and to relate these processes to vocabulary development. Based on the studies reviewed in Chapter 1, Section 6 and Section 7, the main reason for this study was to investigate whether memory for serial order will be more highly correlated with vocabulary development in bilingual children than memory for item identity, as has been found in monolingual children (Majerus, Poncelet, Elsen, et al., 2006) and bilingual adults (Majerus, Poncelet, et al., 2008). To test this hypothesis a longitudinal study was conducted, in a group of bilingual English-German speaking children.

The children were tested once in the beginning of the school year and once at the end of the school year. Monolingual German speaking children were included as comparison group to assess whether memory for serial order also predicts vocabulary acquisition in age matched monolingual peers as reported by Majerus and colleagues (Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006) and to investigate the relationship of item STM to native vocabulary acquisition further. The analysis is split into four parts: Analysis 1 investigates whether serial order STM as measured in the beginning of the school year will be more related to vocabulary development at the end of the school year in bilingual children, as compared to item identity STM, independent of which language is assessed. Analysis 2 looks at the differential effects of item and order STM on vocabulary acquisition in the three subgroups of BL children: native bilinguals, German dominant and English dominant children. Analysis 3 explores whether item and order STM correlate differently with vocabulary acquisition in 7, 8 and 9 year old children. Analysis 4 investigates whether order STM is more related to vocabulary development than item STM in the German monolingual comparison group.

2.1. Methods

2.1.1. Participants

In order to ensure that any differences between bilingual children and monolingual children in their task performances across tasks are not the result of additional instruction or educational demands for the bilingual group, the control children were selected from monolingual schools were a second language is taught but for no longer than three hours per week[17]. Thus, any differences between the bilingual and monolingual children that are observed cannot be due to exposure to learning a second language but should depend on

[17]Note that the ML English children described in Part 2 of this chapter and ML German children described in Part 1 of this chapter were equivalent in their knowledge of a second language.

whether or not children are immersed in a fully bilingual schooling environment and speak both languages fluently.

For the bilingual sample, the school environment in Vienna was completely bilingual (two teachers per class: one English native speaker, one German native speaker; all subjects taught in both English and German).

As far as the home environment characteristics of the sample are concerned, thirty-four children were raised by one parent speaking English and the other parent speaking German (native bilingual). Thirty-two children had stronger German speaking background (German dominant), fifteen children had a stronger English speaking background (English dominant) and two reported that they spoke more than two languages fluently. Approximately 50% of the bilingual group were exposed to English and German from birth (N=45), 36.7% were exposed to German from birth (N=33) and 10% English from birth (N=9). In the opinion of the teachers 82.2% of all children speak German fluently or very well (N=74) and 70% speak English fluently or very well (N=63). Of the ninety bilingual children, forty children were placed in the German group when they started school and fifty were placed in the English group. These groups were chosen by the school in the beginning of year one and focused on one of the two languages more during the first two years. The rationale was, that one of the languages is likely to be more dominant in bilingual children and the more dominant language should be trained more in order to strengthen it. This should give the bilingual child a good foundation in at least one language. All children nevertheless received training in both languages. However, children in the English dominant group might have better English abilities and children in the German dominant group better German abilities. In total, ninety bilingual children from three grades participated in this study. There were twenty-seven children from Year two (13 girls and 14 boys; mean age: 7.46 years; range: 7.00-9.00), thirty from Year three (11 girls and 16 boys; mean age: 8.36 years; range: 8.00-9.05), and thirty one children from Year four (14 girls and 13 boys; mean age: 9.17 years; range: 9.01-10.01).

The children in the German monolingual control group were all recruited in Vienna, Austria, were they went to monolingual primary schools. The children took part in one English class every week. However, all students were learning English in a playful and fun way from the beginning of school and not in an immersion context. None of the children was able to speak English fluently. In total, thirty-six age-matched monolingual German speaking children from grades two, three and four were recruited. The German group included twelve children from Year four (6 girls and 6 boys; mean age: 9.12 years; range: 9.01-10.00), twelve from Year three (7 girls and 5 boys; mean age: 8.13 years; range: 8.01-9.00), and twelve from Year two (6 girls and 6 boys; mean age: 7.28 years; range: 7.00-8.11).

Complete data sets were obtained from 85 bilingual children (due to attrition during the school year[18]) and 36 German monolingual. Parental consent (see Appendix C3 for the Parental Consent Form) was obtained for all children before testing started. All children were tested twice: once at the beginning of the school year (Time 1), and once at the end of the school year (Time 2).

2.1.2. Materials

Receptive Vocabulary Knowledge

English vocabulary knowledge was measured using the BPVS-II (British Picture Vocabulary Scale, L. M. Dunn, Whetton, & Burley, 1997); German vocabulary knowledge was measured using the PPVT-III (Peabody Picture Vocabulary Test, L. M. Dunn, Dunn, Whetton, & Pintilie, 1997) with German words. The raw vocabulary scores from these tests were used as dependent variables in all analyses. Refer to Figure 41 for an example of the BPVS[19].

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[18] Five bilingual children had changed schools or where sick at one of the testing times.

[19] The German version of the PPVT-III used in this study has been translated to use in research by clinical neuropsychologists at the Vienna General Hospital but does not provide norms.

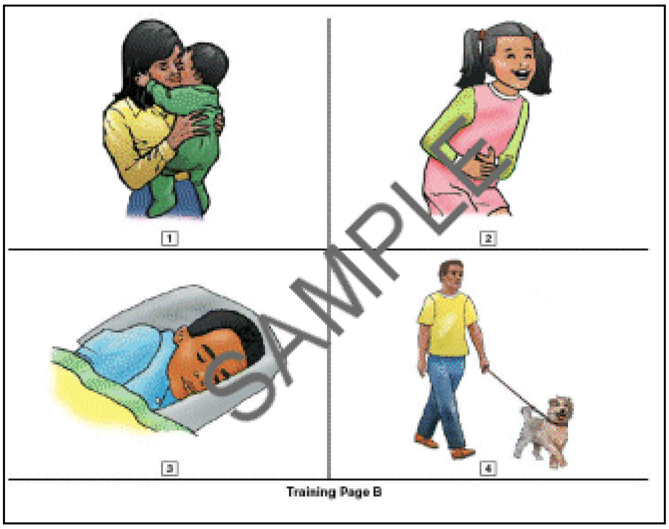

Figure 40: Example of British Picture Vocabulary Scale (BPVS);
Question: "What is sleeping? " Answer "Number 3"

Active Vocabulary Knowledge

Active vocabulary knowledge was measured using pictures taken from Snodgrass and Vanderwart (1980; see Figure 42 for an example). Bilingual children had to name these pictures in both German and English, monolingual children only in their native language. Pictures corresponding to words from the serial order and item STM tasks were included to ensure that the children knew these words (i.e., that familiar words were used in the experimental tasks). See Appendix C1 for details on stimuli and Appendix C7 for task instructions.

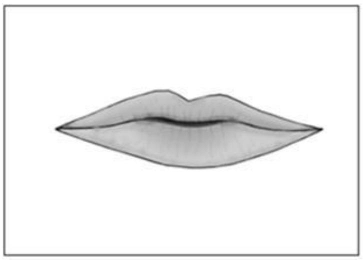

Figure 41: Example of active vocabulary knowledge picture;
Task: "Name the picture."

Non-Verbal Intelligence

Raven's Coloured Progressive Matrices (Raven, 1984) were used to estimate general nonverbal reasoning abilities. Raw scores were used in the analysis. Figure 43 depicts an example.

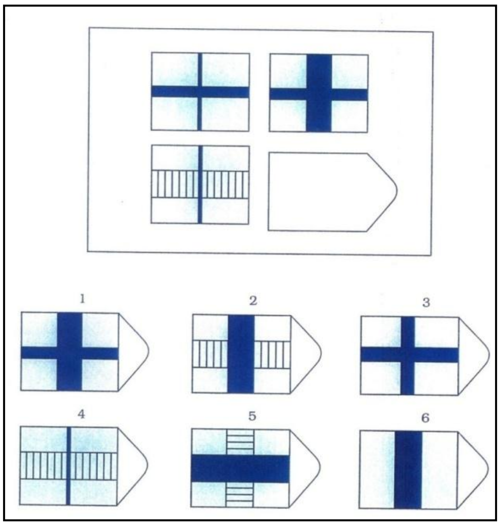

Figure 42: Example of CPM; Question: "Which is the missing piece?"

Verbal Order STM Task: Serial Order Reconstruction Task

This task was designed to maximize order STM skills and minimize item STM demands: One German and one English version of this task were devised[20]. Both tasks consisted of the auditory presentation of word lists of increasing length containing up to seven monosyllabic animal names: whale/Wal, sheep/Schaf, mouse/Maus, hen/Huhn, fish/Fisch, cow/Kuh, and bear/Bär). Parents of bilingual participants were asked to rate the age of acquisition (AoA) of each word for the two languages separately. For the English animal names they reported a mean AoA of 45 months (range: 43-48 month), and according to scores in the Lex2005 database (Dale & Fenson, 1996), toddlers at 30 months were able to name 83.8% of the animals correctly

[20] For more details on stimuli see Appendix C1 and Appendix C7 for task instructions.

(range: 47.1-95.7). Mean lexical frequency based on the CELEX database (COB score) was 378 (range: 100-1438). For the German animal names parents of the bilingual children reported slightly lower AoA scores (mean: 24 months, range: 21-31 months), mean lexical frequency (based on the CELEX database, MANN score) was 48 (range: 2-136). These parameters demonstrate that all items were highly familiar to the children[21].

The seven stimuli were used to form six lists with a length ranging from two to seven items. The inter-stimulus interval was 650ms. Words were recorded by female and male English and German native speakers (one female native English speaker, one female native German speaker, one male native English speaker and one male native German speaker) and stored on computer disk. The mean duration of the German item presentation was 586ms (range: 382-745) and the English was 631ms (range: 413-798).

All words were presented on a computer using JBuilderW. The procedure was as follows: The words were auditorily presented over headphones connected to a Fujitsu Siemens laptop. Two stimuli lists were created for each language (English/German) with a similar order of stimuli. Words were alternately presented by a male and female voice. One list started with a stimulus presented by a female voice, and the other list started with a stimulus presented by a male voice. In this way, each word appeared in one list spoken by a female and in the other list by a male voice. Children listened to either list A or list B. This procedure controlled for possible gender-related differences.

After the auditory presentation of the list of animal names, the child saw pictures of the animals on the computer screen. These pictures were black and white drawings, presented in the centre of the screen. Participants had to click on the pictures in the order that the names had been spoken (see Figure 44 and Figure 45 for examples).

[21] Note that the ratings of parents and the child-specific Lex2005 database entries provide much stronger evidence for the high familiarity of words to the children than data from the CELEX databank, which might not be representative as it is based on adult and not children´s literature.

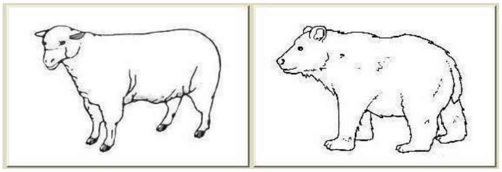

Figure 43: Example of the serial order task: “bear – sheep” – the child had to first click on the bear and then on sheep picture.

Pictures that were clicked were marked as used (greyed out) and hence each picture could only be chosen once. Only pictures for the animals actually presented were shown to the child; thus for list length 2 the child saw two pictures, for list length 3, three pictures, and so forth up to a maximum of seven items. This procedure ensured that item identity information was known in advance and participants only had to remember the position in which each item occurred within the original auditory presentation of the list. After clicking all the pictures the next trial started automatically. After each block, before the lists increased by one additional item, the child was informed, i.e. a motivational picture came up (for example a hand with the thumbs up) and the words “Well done! One more word will now be added to the list of animals – are you ready? Click *here* to continue” appeared.

Figure 44: Example of child experiment setting

The order STM task used in this study is similar to the serial order reconstruction task by Majerus, Poncelet, Elsen, et al. (2006). Serial order reconstruction tasks as opposed to serial order recall tasks have been shown to be relatively independent of language factors such as phonology but to tap into language independent order short-term memory processes (see e.g., Thorn, et al., 2002). For analysis, the number of sequences correctly reconstructed out of a total of 24 sequences in English and German was calculated.

Item STM Task: Rhyme Probe Recognition Task

This task was designed to maximize item STM skills and minimize order STM demands: A German and English version of this task was constructed. Lists of two to seven words were created[22]. Parents of bilingual participants were asked to rate the AoA of English words. They reported an AoA of 46 months (range: 40-52 month), looking at scores in the Lex2005 database toddlers at 30 months were able to name 93.76% of the items correctly (range: 60-100). Mean lexical frequency based on the CELEX database (COB score) was 1868 per million (range: 0-17486). For the German items parents of the bilingual children reported slightly lower AoA scores (mean: 26 months, range: 17-35 months), lexical frequency (based on the CELEX database, MANN score) was 328.25 (range: 9-4337). These parameters ensured that all items were highly familiar to the children[23]. Words were recorded by a male and female human voice (English and German native speakers) and were stored on a computer disk. Mean duration of the German items was 571ms (range: 353-794) and the English 573ms (range: 412-783).

Participants were instructed that they would hear a list of words, followed by a probe word and they would then be asked to judge whether the probe word rhymed with one of the words in the list or not. There were six trials for study lists containing two and three items and seven trials for study lists containing four, five, six, and seven items. The lists of words were presented

[22] For more details stimuli see Appendix C1 and Appendix C7 for task instructions.

[23] Note that the ratings of parents and the child-specific Lex2005 database entries provide much stronger evidence for the high familiarity of words to the children than data from the CELEX databank, which might not be representative as it is based on adult and not children´s literature.

counterbalanced in male and female voice. For each list length there were two negative probe trials in which no words rhymed, and four (five for list lengths four to seven) positive probe trials, in which one word in the list rhymed with the probe word. This procedure was chosen because Majerus, Poncelet, Greffe et al. (2006) reported that non-matching probes (i.e. negative probe trials) were very easily rejected by monolingual adults, while the detection of matching items was much more difficult and yielded a greater variability in memory performance, thus increasing the sensitivity of the task. For the items probed positively, one was in the primacy portion of the list (first item), one in the most recent position of the list (last item) and the others were randomly distributed over the remaining positions in each list.

Before each trial a star appeared on the screen, and the end of each trial was signalled by a 500ms pure tone, followed by the presentation of the probe word. After hearing the probe word, the participants had to press a “green happy smiley” button if the word after the beep rhymed with one of the words heard before or alternatively a “red grumpy smiley” button if the item had not rhymed with any of the words before. Participants were informed every time the sequence length increased. Motivational feedback was given in the form of a picture that showed the thumbs up and the words “Well done” occurred (independent of actual performance).

The item STM task was adapted from the item STM task developed by Majerus, Poncelet, Greffe, et al. (2006). Rhyme probe recognition tasks are thought to tap into language dependent item information short-term memory processes (Majerus, Poncelet, et al., 2008). They have been shown in previous studies to specifically measure phonological retention capacities without requiring explicit retention of serial order information (e.g., Freedman & Martin, 2001; Majerus, Van der Linden, Poncelet, & Metz-Lutz, 2004; Majerus, Van der Linden, & Renard, 2001; Martin, Shelton, & Yaffee, 1994).

The proportion of correct responses over all forty experimental trials was then calculated for each child. All tasks were presented as games[24].

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[24] For more details on instructions see Appendix C7.

2.1.3. Procedure

Parental consent was obtained for each child (see Appendix C2). The parents were administered a questionnaire[25] to assess whether their child(ren) had a history of neurological disorders or neuro-developmental delays, that auditory and visual acuity were normal and that the child had normal language development and no learning difficulties. Family socio-economic background was considered and was relatively homogenous. For bilingual children an additional question was whether the children's native language was either German and/or English. In addition, teacher questionnaires (see Appendix C5) were handed out in the beginning of the school year to get the teachers' opinion about each child´s language level.

For both the bilingual children and the German monolingual control group the study was carried out in two stages: The first stage was conducted at the beginning of the school year (September – December). Older children (Year 4) were tested before younger children (Year 2), children in Year 3 were tested in between Year 2 and 4.

At the first stage (September – December) each child took part in a first session that included active and passive vocabulary tests and item and order STM tasks. For bilingual children teacher and parental questionnaires were processed and in addition to the German session, where tasks were administered in German, each bilingual child also took part in an English session (so both their native and second language was covered). These sessions were completed in counterbalanced order (some started with English and some with German).

In the second stage, conducted at the end of the school year (April – May), one session per child was conducted where once again, active and passive vocabulary (for the bilingual children in both English and German) was measured, as well as non-verbal IQ.

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[25] For details see Appendix C3 and Appendix C4 for detailed results of the questionnaire.

At each stage of testing every child was tested individually in a quiet room. Each testing session lasted approximately 45 minutes per child to reduce fatigue. In the first session (beginning of the school year) bilingual children participated in two sessions which took place one week apart. One session consisted of tasks administered in English, the other in German. Sessions were counterbalanced across children. Monolingual children participated in one session only (in their native language).

2.1.4. Order of Task Administration

Participants were all tested in a one-to-one setting with the experimenter. For the bilingual children, two sessions took place in the beginning of the school year, each session lasting about 45 minutes and the sessions were one week apart. Sessions were split by language: Half of the bilingual children started with the English tasks (English active and passive vocabulary, English item STM and order STM tasks) and the other half started with the German tasks (German active and passive vocabulary, German item STM and order STM tasks). Session three took place at the end of the school year and involved the non-verbal IQ screening and English and German active and passive vocabulary tests. Again, half of the children did the English tasks first, and the other half of the children the German task in a single session. See Figure 46 for order of task administration.

German monolingual children only took part in one session at the beginning of the school year (in their native language German), and one session at the end of the school year.

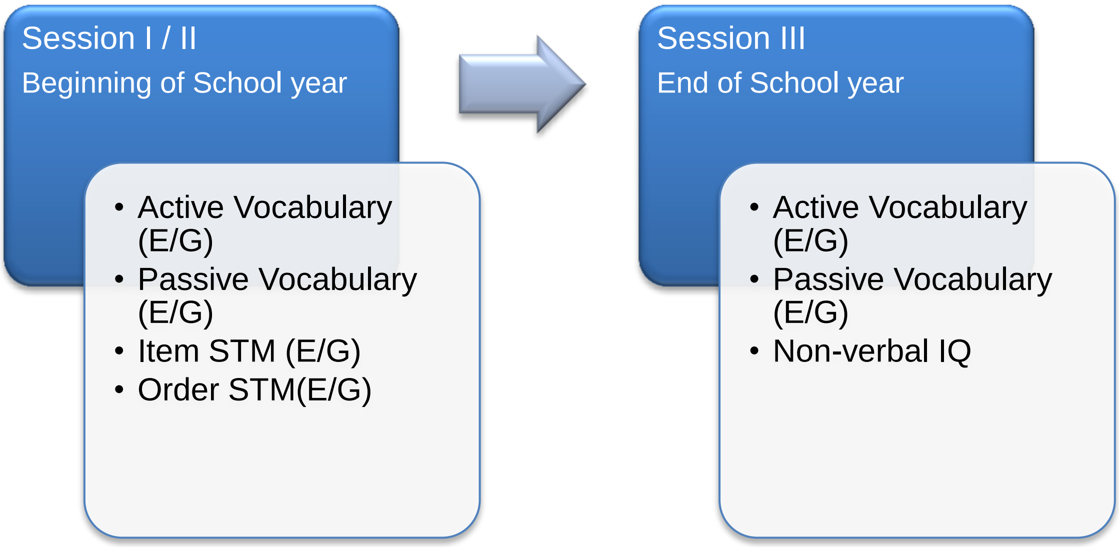

Figure 45: Order of task administration

2.2. Results

2.2.1. Analysis 1: Item and Order STM and their Relation to Vocabulary Acquisition in Bilingual Children

According to Gupta and MacWhinney (1997), Gupta (2003) and Majerus et al., (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Majerus, Poncelet, et al., 2008) significant correlations between measures maximizing retention of serial order information (order STM tasks) and vocabulary development can be expected in both bilingual children and the monolingual comparison group. Based on previous research (see e.g. Majerus, Poncelet, et al., 2008; for a review see Section 6.1. and 7 in Chapter 1) one of the predictions is that if order STM is indeed more important for new word learning, this finding should be consistent across languages in bilingual children (see e.g. Thorn and Gathercole, 1999; and for models supporting this hypothesis see Burgess and Hitch, 1992, and Gupta, 2003, who postulated the existence of a STM system solely dedicated to the storage of serial order information). However, note that (as pointed out in Chapter 1, Section 3) the natures of the languages spoken by bilingual participants might influence the tasks differently. On the basis of the research described above it was predicted that STM for serial order will be more related to vocabulary development at the end of the school year (Time 2) in bilingual children, as compared to STM for item identity, independent of which language is assessed[26].

2.2.1.1. Results

Descriptive statistics are reported in Table 4.

A mixed ANOVA with time (beginning of the school year and end of the school year) and group (ML German and BL children) as between participant factors and with German passive vocabulary (PPVT-III) as within participant factor showed a significant time by group interaction $F(1,119)=5.195$, $p=0.024$: At the beginning of the school year (Time 1) German ML children (ML Time 1 mean=81%, SE=0.97) outperformed bilingual children (BL Time 1 mean=74%, SE=1.32) in German passive vocabulary skills, but there was no significant difference between groups by the end of the school year (BL Time 2 mean=81%, SE=0.97; ML Time 2 mean=81%, SE=1.48). A mixed ANOVA with the same between participant factors (time and group) and with German active vocabulary (Picture Naming) as a within participant factor revealed a main effect of time $F(1,119)=19.255$, $p<0.001$ showing an increase from the beginning of the school year (Time 1 mean=98%, SE=0.54) to the end of the school year (Time 2 mean=99%, SE=0.38) with both German ML and BL children performing similarly across the school year.

In a cross sectional analysis of the data collected at the end of the school year for English speaking groups, ML English children outperformed BL children in passive English vocabulary knowledge, BPVS 2, $F(1,114)=30.317$, $p<0.001$. No differences were found in active vocabulary knowledge (Picture Naming) between English ML children and BL German-English children.

[26] Data at the end of the school year (Time 2) were analysed to take existent vocabulary knowledge from the beginning of the school year (Time 1) into account.

	English ML children (N=31)	German ML children (N=36)	Bilingual children (N=85)	Native Bilingual (N=36)	German dominant (N=34)	English dominant (N=15)
Passive German vocabulary knowledge, Time 1 (PPVT 1)		77.34 (8.46)	73.27 (13.68)	72.71 (12.82)	79.16 (8.31)	61.73 (17.71)
Passive German vocabulary knowledge, Time 2 (PPVT 2)		80.54 (8.84)	80.55 (8.93)	80.64 (6.74)	83.84 (3.64)	72.91 (15.64)
Passive English vocabulary knowledge, Time 1 (BPVS 1)			42.74 (9.67)	45.57 (8.84)	38.40 (9.79)	45.31 (8.26)
Passive English vocabulary knowledge, Time 2 (BPVS 2)	56.68 (9.04)		46.56 (8.66)[27]	49.47 (7.7)	43.03 (9.21)	47.58 (6.95)
Picture naming German, Time 1		95.58 (1.90)	96.84 (6.49)	98.11 (3.36)	98.49 (2.14)	90.13 (12.32)
Picture naming German, Time 2		99.78 (0.73)	98.22 (4.46)	98.86 (2.07)	99.47 (1.23)	93.85 (8.92)
Picture naming English, Time 1			96.84 (6.48)	94.13 (6.29)	81.81 (10.22)	97.69 (3.83)
Picture naming English, Time 2	92.56 (3.00)		91.58 (9.00)	96.29 (4.60)	83.79 (8.72)	97.95 (2.41)
Non verbal IQ screening (CPM)	62.95 (10.44)	82.64 (10.23)	84.90 (9.19)	85.57 (9.29)	85.46 (8.57)	82.04 (10.39)
Item STM German		69.93 (10.88)	72.83 (12.79)	72.76 (12.60)	73.43 (13.39)	71.72 (12.67)
Item STM English	71.29 (13.58)		66.19 (12.10)	65.71 (12.38)	65.29 (11.61)	69.38 (12.73)
Order STM German		54.21 (11.75)	51.31 (11.95)	58.06 (11.17)	59.16 (14.43)	59.06 (11.38)
Order STM English	41.86 (7.42)		49.69 (11.35)	48.97 (9.91)	49.14 (13.32)	52.66 (10.06)

Table 4: Descriptive statistics for all children showing percentage correct (SD) for each task.

[27] The score difference in PPVT and BPVS might be explained by the fact that BPVS-II in English uses more difficult vocabulary (lower lexical frequency) compared to the German version of the PPVT-III. Unfortunately, no data on lexical frequency of the German words used in this version of the PPVT used in this study is available as this time. The PPVT-III was translated into German from US American English by a team of neuropsychologists from the Vienna General Hospital for internal research purposes.

It was not possible to investigate test-retest reliability for the tests as they were only administered once, at the beginning of the school year. However, note that Majerus et al., 2006, report a high test-retest reliability of .82 for the serial order reconstruction task. For further analysis of intercorrelations between tests used in this thesis to investigate internal consistency reliability, please refer to Part 2 of Chapter 5.

A mixed ANOVA with school year (Year 2, 3, and 4) and group (ML German, ML English and BL) as between participant factors and task (item and order STM) as within participant factors was conducted. Covariates were age, gender, handedness and average passive vocabulary score in the native language. A significant task by group interaction was found, $F(2,138)=8.95$, $p<0.001$, with better performance on the order tasks for bilinguals (order mean=20.06, SE=0.439) compared to the German ML (order mean=18.34, SE=0.771) and the English ML (order mean=17.31, SE=0.765) groups. An unexpected finding was significantly better performance on the item identity task for the English ML (item mean=29.39, SE=0.865) compared to the ML German (item mean=27.01, SE=0.873) and the BL children (item mean=27.82, SE=0.497).

In order to examine the relationship between vocabulary knowledge at the end of the school year (Time 2) and item and order STM, simultanious multiple regression analysis was used. The dependent variables were either English or German passive vocabulary at the end of the school year (BPVS II / PPVT II)[28]. Independent variables were age, gender, handedness, non-verbal IQ, English and German active and passive vocabulary skills in the beginning of the school year, English and German item STM, and English and German order STM scores. Vocabulary scores from the beginning of school (PPVT I and BPVS I) were taken into account to control for initial differences in vocabulary knowledge.

In order to predict English vocabulary learning in BL children simultaneous multiple regression analysis was conducted. The regression analysis was statistically significant ($F(14,84)=8.616$, $p<.001$, adjusted $R^2=.56$) with active

[28] These scores were used as these tests were more sensitive than active vocabulary scores as they showed a greater range of performances (BPVS II also provided test norms and PPVT II was the German equivalent to BPVS II).

and passive English vocabulary at Time 1, as well as order STM in English being significant predictors of Time 2 English vocabulary (see Table 5 for details). Thus, memory for serial order in English as well as extant vocabulary contributed to English vocabulary acquisition in the bilingual children.

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	***Std. Error***	***Beta***		
Age Time 1	1.775	0.979	0.161	1.812	0.074
Passive vocabulary German Time 1	0.044	0.072	0.068	0.609	0.544
Passive vocabulary English Time 1	**0.517**	**0.086**	**0.580**	**5.999**	**0.000**
Active vocabulary German Time 1	0.049	0.132	0.036	0.373	0.710
Active vocabulary English Time 1	**0.174**	**0.087**	**0.207**	**2.007**	**0.049**
Gender	0.440	1.459	0.025	0.302	0.764
Handedness	4.121	2.384	0.132	1.728	0.088
Non-verbal IQ	-0.055	0.083	-0.058	-0.664	0.509
Item STM English	-0.034	0.068	-0.050	-0.493	0.624
Item STM German	0.010	0.067	0.014	0.143	0.887
Order STM German	0.052	0.172	0.073	0.302	0.764
Order STM English	**0.340**	**0.148**	**0.450**	**2.292**	**0.025**

Table 5: Multiple regression analysis predicting Time 2 English vocabulary knowledge in bilingual children

For German language acquisition, a different pattern emerged: The regression analysis was also statistically significant, $F(13.29)=14,84$, $p<.001$, adjusted $R^2=.67$) but only active and passive German vocabulary at Time 1 were significant predictors of Time 2 German vocabulary knowledge (see Table 6 for details). Clearly, existing lexical knowledge is the best predictor of subsequent vocabulary acquisition in German. Neither memory for serial order nor item identity predicted a significant amount of variance in German vocabulary scores (see Table 6).

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Age Time 1	1.520	0.871	0.134	1.744	0.086
Passive vocabulary German Time 1	**0.282**	**0.064**	**0.425**	**4.405**	**0.000**
Passive vocabulary English Time 1	0.137	0.077	0.149	1.786	0.078
Active vocabulary German Time 1	**0.518**	**0.118**	**0.365**	**4.408**	**0.000**
Active vocabulary English Time 1	-0.119	0.077	-0.137	-1.543	0.127
Gender	0.402	1.298	0.023	0.310	0.758
Handedness	1.856	2.121	0.058	0.875	0.384
Non-verbal IQ	-0.013	0.074	-0.014	-0.179	0.859
Item STM English	-0.034	0.061	-0.049	-0.565	0.574
Item STM German	0.017	0.059	0.024	0.292	0.771
Order STM German	-0.085	0.153	-0.116	-0.554	0.581
Order STM English	-0.074	0.132	-0.095	-0.558	0.579

Table 6: Multiple regression analysis predicting Time 2 German vocabulary knowledge in bilingual children

2.2.1.2. Interim Discussion

Multiple regression analysis supported the primary hypothesis that order STM is a significant predictor of vocabulary acquisition in bilingual children: English vocabulary learning was predicted by English order STM when taking vocabulary knowledge at the beginning of the school year (Time 1) into account. This is in line with previous findings (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Majerus, Poncelet, et al., 2008). However, the finding was not consistent across vocabularies– for German vocabulary development, only existing German active and passive vocabulary at the beginning of the school year accounted significantly for vocabulary at the end of the year. Hence order STM was a predictor of vocabulary learning in English, but not German, i.e. it predicted vocabulary at the end of the year in the less dominant language, but not the dominant language in terms of environmental exposure (German is the language of the country the children live in while English might only be spoken at school or at home).

There are several possible reasons for this pattern of results. The children in our sample might have been not the appropriate age group to investigate (for analyses of the separate age groups see Section 2.2.3. this chapter). As pointed out by Majerus, Poncelet, Greffe, et al. (2006) and Gathercole, Willis, Emslie and Baddeley (1992) order STM (or verbal STM in general) might only be the better predictor of vocabulary growth in children below the age of 6. After that age, research suggests that existing vocabulary knowledge becomes the major predictor of further vocabulary development (Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). This has been explained by substantially increased vocabulary knowledge leading to more segmentalized phonological representations which in turn will then begin to facilitate processing of phonological item information in verbal STM tasks (Majerus, Poncelet, Greffe, et al., 2006; see also Metsala, 1999). Hence, it might be that in the children tested by us, German vocabulary knowledge had already increased substantially and order STM was only able to predict vocabulary growth in their less dominant language: English. As argued by Majerus, Poncelet, Greffe, et al. (2006), entering school might put renewed pressure on vocabulary development as the child will be confronted with much higher rates of new words than ever before. In our sample this is especially true for the English language, as German is the language of environment the children are used to.

Another reason for different effects of the different predictor variables in the two languages may be that there were subtle differences in the children's proficiency in the two languages. In the present study German was the language the bilingual children were more exposed to, as it is the language of the environment they live in. English on the other hand was mainly used at school, at home and when playing with friends. Note that all children were highly proficient in both English and German, as indicated by vocabulary knowledge as tested with active and passive vocabulary tests (see Table 4 for descriptive statistics). It is not sensible to compare the test results of the passive vocabulary tests (English: BPVS, German: PPVT) statistically as they were tested by two completely different tests with only BPVS providing age related norms. However, when looking at active vocabulary tests (the same pictures had to be named in both languages), it was found that overall the BL children were better at the German than the English picture naming tasks (English mean: 90 % correctly named, German mean: 97% correctly named, $t(88)=5.217$, $p<.001$). This could strengthen the argument that the BL children in our sample are better at German as compared to English (even though they are highly proficient at both languages).

Another potentially relevant factor is the distinct structure of each of the two languages: German, when compared to English, shows more flexibility of word order. For example it allows for compound nouns (i.e. combining many single nouns to one big noun, i.e. Donaudampfschiffkapitänkajütenschlüssel, meaning the “key to the cabin of the captain of a steam boat that runs on the river Danube”) and sentence structure is more flexible. This might enhance order STM skills in German, which might make it a less powerful predictor variable (simply because speaking German “exercises” order STM). Note that as children get older it stops being a predictor in English too. This indicates that the BL children in this sample might get their experience earlier in German compared to English.

To investigate language-effects further, the next analysis explores the three different subgroups of BL children separately: Native BL, German dominant and English dominant children.

2.2.2. Analysis 2: Language Dominancy Effects in Item and Order STM and Vocabulary Acquisition in BL children

Analysis 2 further investigates the findings of Analysis 1. As noted in the method section of Analysis 1, the sample of bilingual children can be divided into three subgroups: native bilingual children, who are exposed to both languages equally, dominant German children, with relatively more exposure to

German, and dominant English children with relatively more exposure to English.

It was previously found that order STM was a useful predictor for English vocabulary at the end for the school year but this was not found for German. If this finding arose because the sample was more exposed to German (i.e. German was the more dominant language, L1) and less exposed to English (i.e. English was the less dominant language, L2) then the effect of order predicting English vocabulary should be biggest in those whose English vocabulary knowledge was worst, i.e. German dominant children. For this group entering school will have put the highest pressure on vocabulary acquisition in English, as the children were confronted with much higher rates of new English words than the other groups (see also Majerus, Poncelet, Greffe, et al., 2006). A similar pattern might be found for the English dominant children just with German vocabulary (less dominant language) and not English vocabulary (dominant language). Native BL children enter school with similar vocabulary knowledge in both languages. Hence pressure put on vocabulary acquisition in German and English is similar in both languages and importantly less strong as compared to German or English dominant BL children, i.e. for their non-dominant language.

On the basis of the outcome of the first analysis and the research described above, it was predicted that STM for serial order would be more highly correlated to vocabulary development at the end of the school year (Time 2) in the less dominant language, i.e. English order STM might be related to English vocabulary in German dominant bilingual children and German order STM might be related to German vocabulary in English dominant children. No differences were expected in the native bilingual children.

In addition it has been found that with ML children over 6 years of age, vocabulary knowledge became the dominant “pacemaker” in language development (Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). Hence a correlational analysis was also performed between active and passive vocabulary knowledge at Time 1 and Time 2. High correlations were expected between vocabulary in a given language at Time 1 and Time 2.

2.2.2.1. Results

In order to examine the effect of language dominancy on the relationship between the vocabulary measures at the end of the school year (Time 2) and item and order STM for the three different language groups of BL children (Native bilingual, German dominant and English dominant children) partial correlations were calculated[29]. The first set of partial correlation (r^{par1}) controlled for residual age effects and nonverbal IQ. The next set of partial correlations additionally controlled for active and passive vocabulary knowledge at Time 1 (r^{par2}) in order to investigate if possible initial correlations of item and order STM can be explained by existent vocabulary knowledge. Results are shown in Table 7.

As predicted, significant correlations were observed for the BL children in their less dominant language (r^{par1}). German order STM correlated marginally with German passive vocabulary at Time 2 in English dominant BL children ($r=.549$, $p=.052$). In German dominant BL children, English order STM correlated highly with English passive vocabulary at Time 2 ($r=.397$, $p=.024$). No correlations were found between item and order STM tasks and native BL children. Note that the correlations could be explained by existent vocabulary knowledge at Time 1 as when taking active and passive vocabulary in English and German into account they no longer remained significant (r^{par2}).

When looking at the correlations of vocabulary knowledge at Time 1 and vocabulary knowledge at Time 2, English vocabulary knowledge at Time 1 was highly correlated to English vocabulary knowledge at Time 2 and German vocabulary knowledge at Time 1 was highly correlated to German vocabulary knowledge at Time 2 in all three subgroups of BL children.

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[29] Unfortunately conducting multiple regression analysis as in Analysis 1 (see Section 2.2.1.) was not sensible due to the relatively small group sizes.

	English Dominant (N=15)				German Dominant (N=35)				Native Bilingual (N=39)			
	English Time 2		**German Time 2**		**English Time 2**		**German Time 2**		**English Time 2**		**German Time 2**	
	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}
Item STM English	-.123	-.116	.248	.032	.264	.184	-.077	-.142	-.065	.141	-.050	.205
Order STM English	.065	.141	.289	.078	**.397* (p=.024)**	.210	.217	.014	.112	.206	-.041	.169
Item STM German	.026	-.161	.326	.152	.272	.044	.231	.022	-.030	.180	-.161	-.037
Order STM German	.425	.364	.549 (p=.052)	.432	.208	.159	.253	.136	.127	.241	-.043	.164
English Time 1	**.824* (p=.001)**		.229		**.665** (p<.001)**		.335 (p=.061)		**.741** (p<.001)**		.314 (p=.071)	
German Time 1	.520 (p=.068)		**.704* (p=.007)**		.338 (p=.059)		**.507* (p=.003)**		.188		**.662** (p<.001)**	

Table 7: Partial correlation between passive vocabulary knowledge and the different predictor tasks for the three language groups of BL children; *p<.05, **p<.001

2.2.2.2. Interim Discussion

As hypothesized, language dominancy had an effect on which variables correlated significantly with vocabulary at Time 2 in BL children. STM for serial order was more highly correlated to vocabulary development at the end of the school year (Time 2) in the less dominant language. Even though the effects were only subtle (which is likely due to reduced statistical power due to the small group size), German order STM was correlated to German vocabulary acquisition in English dominant BL children. In German dominant BL children, English order STM was significantly correlated to English vocabulary acquisition. Note that most of the correlations could be explained by existent vocabulary knowledge.

The finding is in line with previous research, that order STM correlates with vocabulary acquisition (see Section 6.1. in Chapter 1 for an extensive review). Majerus, Poncelet, Greffe et al. (2006) found that order STM was correlated with vocabulary knowledge in ML children aged 4 and 6 years old. Digit span was significantly correlated with vocabulary knowledge in 6 year old English ML children in a study by Gathercole et al. (1992). Importantly, the data in this analysis strongly suggest that order STM seems to be especially important when pressure is put on vocabulary learning. They further indicate that order STM is important for new word learning, independent of which language (i.e. German or English), or in other words, German itself does not enhance order STM (as argued in Section 2.2.1.2., this chapter) but rather the fact that pressure is put on vocabulary learning in a given language. The findings might possibly imply that the results of Analysis 1, which found that performance on order STM tasks predicted English but not German vocabulary at the end of the school year (see Section 2.2.1. this chapter), could be due to the fact that the children were more exposed to German (i.e. German was the more dominant language, L1) and less exposed to English (i.e. English was the less dominant language, L2).

Studies of bilingual speakers suggest that while phonological STM capacity seems to be an important early predictor of second language learning, vocabulary knowledge becomes the main factor that drives lexical learning in learners with considerable familiarity in a second language (e.g. Cheung, 1996; Gathercole, et al., 2001; Masoura & Gathercole, 2005; Thorn & Gathercole, 1999; see Section 7, Chapter 1, for an extensive review). In order to understand the associations of STM and vocabulary better the next analysis investigates age-effects in the three different age-groups of BL children: Children in Year 2, 3 and 4 of primary school, aged 7, 8 and 9 years old.

2.2.3. Analysis 3: Age Effects in Item and Order STM and Vocabulary Acquisition in BL Children

A recent study by Majerus, Poncelet, Greffe, et al. (2006) showed that the relative importance of memory for serial order and memory for item identity on vocabulary acquisition can change with age. Here, the three different age groups of bilingual children individually: 7, 8 and 9 year-olds (Year 2, 3 and 4 in primary school) are analysed.

Previous research has shown that the relation between general verbal STM measures and vocabulary acquisition is strongest at around 4 to 6 years (Bowey, 1996; Gathercole & Adams, 1993, 1994; Gathercole & Baddeley, 1989; Gathercole, et al., 1997; Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). At later ages, the association tends to be less pronounced as vocabulary growth will be more influenced by external factors such as school instruction and reading experience (Cunningham & Stanovich, 1991; Gathercole & Baddeley, 1993; Gathercole, et al., 1999). In this study 7- to 9- year old children were investigated. From what we know of previous research, it is hypothesised that only at younger ages (i.e. Year 2), will order STM correlate with vocabulary at Time 2, while at later ages (i.e. Year 3 or 4) existing vocabulary might become a better predictor.

In addition (as argued in Section 2.2.2.), high correlations were expected between vocabulary in a given language at Time 1 and Time 2 in each Year.

2.2.3.1. Results

Partial correlations[30] between vocabulary knowledge at Time 2 and the item and order STM task were conducted separately in each of the three age groups: The first set of partial correlation (rpar1) controlled for nonverbal IQ. The next set of partial correlations additionally controlled for active and passive vocabulary knowledge at Time 1 (rpar2) in order to investigate if possible initial correlations of item and order STM can be explained by existent vocabulary knowledge. Results are shown in Table 8.

As predicted, significant correlations were observed for the BL children in Year 2 and 3 but not Year 4. In Year 2, performance on the order STM in English (r=.490, p=.046) and marginally German (r=.435, p=.081) correlated with English vocabulary at Time 2 but no correlations were found between item or order STM and German vocabulary at Time 2. In Year 3, English order STM (r=.490, p=.018) and German order STM (r=.388, p=.031) correlated highly with English vocabulary at Time 2. No significant correlations between item or order STM and vocabulary scores for English and German at the end of the school year were found for Children in Year 4. When taking into account extant active and passive vocabulary knowledge in English and German at Time 1, English order STM remained significantly correlated to English vocabulary at Time 2, and German order STM correlated marginally with English vocabulary at Time 2. In Year 3, only English order STM remained marginally correlated to English vocabulary at Time 2

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[30] As in Section 2.2.2., conducting multiple regression analysis as performed in Analysis 1 (see Section 2.2.1.) was not sensible due to the relatively small group sizes.

	Year 2 (N=23)				**Year 3 (N=37)**				**Year 4 (N=25)**			
	English Time 2		**German Time 2**		**English Time 2**		**German Time 2**		**English Time 2**		**German Time 2**	
	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}	r^{par1}	r^{par2}
Item STM English	.341	.208	.135	.032	-.031	-.036	-.096	.086	-.024	.170	-.120	-.089
Order STM English	**.490* (p=.046)**	**.451* (p=.040)**	.108	.027	**421* (p=.018)**	**.298 (p=.082)**	-.027	.259	-.257	-.233	-.084	-.113
Item STM German	.255	.209	.203	.110	.071	.074	.090	.143	-.052	.034	-.222	-.175
Order STM German	**.435 (p=.081)**	**.401 (p=.072)**	.292	.262	**.388* (p=.031)**	.264	279	.266	-.285	-.277	.012	.019
English Time 1	**.499* (p=.018)**		.138		**.705** (p<.001)**		.046		**.842** (p<.001)**		.074	
German Time 1	.281		**.782** (p<.001)**		-.053		**.536* (p=.001)**		.215		**.685** (p<.001)**	

Table 8: Partial correlation between passive vocabulary knowledge and the different predictor tasks for the three age groups of BL children; *p<.05, **p<.001

2.2.3.2. Interim Discussion

Only in the younger two age groups (Year 2 and 3 but not Year 4) did order STM correlate significantly with English vocabulary scores at the end of the school year. In Year 2, the correlation between English order STM and English vocabulary at Time 2 remained significant after taking into account extant active and passive vocabulary knowledge. This finding is in line with previous research which suggests that whilst (order) STM is a good predictor of vocabulary growth in younger children, later on existing vocabulary knowledge becomes the stronger predictor (Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). Again, in the overall group with all language-dominancy levels mixed, the correlations were only found for English vocabulary and not for German vocabulary. Possible reasons for this discrepancy were discussed in the interim discussion of Analysis 2.

It would be interesting to investigate this developmental question within the three different language dominant groups (German dominant, English dominant or native BL children). However this would leave the groups too small to be analyzed. Future research could look into this question further.

2.2.4. Analysis 4: Item and Order STM and their Relation to Vocabulary Acquisition in Monolingual Children

The aim of this final analysis was to determine whether German ML age-matched children show a similar relationship between vocabulary acquisition and order STM as found in the English/German BL children. In particular, the analysis sought to establish whether order STM is correlated more highly with vocabulary acquisition in 7 to 9 year old ML German children, compared to item STM, as has previously been found to be the case in younger ML French speaking children (see e.g., Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006).

As pointed out in Analysis 1 (see Section 2.2.1.), strong correlations between measures maximizing retention of serial order information (order STM tasks) and vocabulary development can be expected also in ML children. However, previous studies with monolingual children have not shown consistent results: Majerus, Poncelet, Greffe, et al. (2006) found that order STM and not item STM was related to vocabulary acquisition in 4 and 6-year old French ML children, but in 5-year olds item STM and not order STM predicted vocabulary acquisition. A longitudinal study following the 4 year old French ML children for one year found order STM to be the strongest predictor of the increase of vocabulary knowledge when also taking into account item STM, vocabulary knowledge, age and non-verbal IQ (Leclercq & Majerus, 2010). In ML adults, order STM was found to be the strongest predictor of new-word learning (Majerus, Poncelet, Elsen, et al., 2006). In addition, as pointed out in Analyses 2 and 3 (see Sections 8.2.2. and 8.2.3.), in previous research with ML children over 6 years of age, vocabulary knowledge became the dominant predictor variable in language development (Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). Hence the correlational analysis was also performed between active and passive vocabulary knowledge at Time 1 and Time 2.

No study has yet investigated item and order STM in German ML children aged 7 to 9. As previous studies with ML children tended to find order STM to be stronger correlated to value vocabulary knowledge than item STM, it was predicted that serial order STM and not item STM will be more related to German vocabulary knowledge at the end of the school year in ML children. However, note that these studies were all conducted with younger children speaking French not German.

2.2.4.1. Results

Like in Analysis 2 (Section 2.2.2.) and Analysis 3 (Section 2.2.3.), partial correlations were calculated[31] in order to examine the relationship between vocabulary knowledge at the end of the school year (Time 2) and item and order STM. The first set of partial correlation (r^{par1}) controlled for residual age effects and nonverbal IQ. The next set of partial correlations additionally controlled for active and passive vocabulary knowledge at Time 1 (r^{par2}) in order to investigate if the initial correlation of item and order is explained by existent vocabulary knowledge. Results are shown in Table 9.

Significant correlations were observed in ML German children between performance on the German item STM task and German passive vocabulary at Time 2 (r=.334, *p*=.05) but no correlations were found between German order STM and German vocabulary at Time 2. However, the correlation between German item STM and German vocabulary knowledge at Time 2 no longer remained significant when taking active and passive vocabulary in English and German into account (r^{par2}=.203, p=.243).

German vocabulary knowledge at Time 1 was strongly correlated to German vocabulary at Time 2 (r=.679, p<.001).

	German Passive Vocabulary Knowledge Time 2	
	r^{par1}	**r^{par2}**
Item STM German	**.334* (p=.050)**	**.203**
Order STM German	.078	-.196
German Time 1	**.679** (p<.001)**	

Table 9: Partial correlation between passive vocabulary knowledge and the different predictor tasks for ML German speaking children; *p<.05, **p<.001

[31] Unfortunately conducting multiple regression analysis like in Analysis 1 (see Section 2.2.1.) was not sensible due to the relatively small group size (N=36).

2.2.4.2. Interim Discussion

The results of this correlational analysis in ML German speaking children showed that German item STM and German active vocabulary at Time 1, but not German order STM are strongly correlated to German passive vocabulary knowledge at Time 2. The correlation between German item STM and vocabulary knowledge at Time 2 could be explained by existent German vocabulary knowledge at Time 1.

The results suggest that item STM is important for vocabulary development in German ML primary school children aged 7 to 9 years but most of the correlation can be explained by existent German vocabulary. In order to find out whether item STM can predict vocabulary knowledge at a later time point, multiple regression analysis would need to be conducted[32]. Unfortunately the sample is too small to conduct sensible multiple regression analysis.

Previously, item STM had been found to be an important predictor of vocabulary learning in 5 year old French ML children whereas serial order STM measures made no significant independent contribution (Majerus, Poncelet, Greffe, et al., 2006; for a detailed description of this study please refer to Section 6.1., Chapter 1). The authors suggest that this developmental change in relations between vocabulary knowledge and verbal STM measures can be explained by the pressure on vocabulary development, i.e. order STM is most important when high pressure is put on vocabulary learning, e.g. in young children newly acquiring language, or when new vocabulary needs to be learned quickly, e.g. at school entrance or when learning a second language.

The results of Morra and Camba (2009) may be relevant to this finding: They investigated which components predicted vocabulary learning in primary school children aged 8 to 10 years old. The children were all monolingual Italian

[32] Correlation quantifies the degree to which two variables are related but does not fit a line through data points. It computes a correlation coefficient (r), that shows how much one variable tends to change when the other one does. Multiple regression analysis on the other hand finds the best line that predicts Y from X.

speakers whose only experience with foreign languages was some teaching of English provided by the school. This makes Morra and Camba´s participant group very similar to the children used in this study. The components picked by Morra and Camba to predict vocabulary learning included tests of vocabulary, phonological sensitivity (measured with tasks such as nonword repetition, syllable discrimination, syllable repetition and rhyme oddity discrimination, initial syllable oddity discrimination) and “M Capacity” which was thought to reflect general-purpose attentional resources and was defined as major constituent of working memory capacity. It included tests such as counting span, backward digit span and figural intersections test. A nonword learning paradigm was used where the children had to learn picture-nonword pairs. The nonwords varied in length (2-4 syllables) and phonology (native sounding vs. including one Russian phoneme). Linear structural equation analysis showed that phonological sensitivity, vocabulary knowledge and “M Capacity” influenced vocabulary learning but the extent of their contributions depended on specific characteristics of the nonwords to be learned. Phonological sensitivity predicted learning of all nonword types except short native nonwords, vocabulary predicted learning of only short native nonwords and “M Capacity” predicted learning of short nonwords but not long nonwords. These findings raise the question of whether item and order STM might be important for learning of different word types, possibly related to the language learned itself. German for example has much longer words than English (see Section 2.2.1.2. this chapter for more details). Hence we could conclude from Morra and Camba´s study (2009) that, for German, phonological sensitivity, i.e. item STM, could be more important as this factor predicted learning of long nonwords in the Morra and Camba study.

However, this raises the question why the German dominant BL children did not show similar results. This could be due to the fact that they also speak English and hence hold a different vocabulary pool compared to the ML German children and more importantly possibly use different learning strategies.

2.2.5. Summary of the Key Findings of Section 1

In bilingual children there is a specific contribution of serial order processing capacities to vocabulary development in English, but not German. Analysis of the subgroups of BL children revealed that order STM was strongly correlated to vocabulary at Time 2 in the less dominant language, i.e., English order STM was strongly correlated to English vocabulary growth in German dominant BL children and German order STM was strongly correlated to German vocabulary at Time 2 in English dominant BL children. Further analysis showed that this relationship of order STM and vocabulary development in English was especially true for younger BL children aged 7 (Year 2) and 8 years old (Year 3). The second main finding was that in ML German children item STM but not order STM was significantly correlated to vocabulary knowledge at Time 2.

Existent vocabulary at Time 1 was able to explain most of the significant correlations between item and order STM and vocabulary knowledge at Time 2. Only in children aged 7 (Year 2) the correlation between English order STM and English vocabulary at Time 2 remained significant even after taking into account existent vocabulary knowledge at Time 1 ($r=.564$, $p=.01$). This strengthens the claim that after a certain age (or after acquiring a certain level of vocabulary knowledge), vocabulary knowledge itself might become the dominant predictor in language development as previously found in other studies (see e.g. Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006).

3. Part 2: Item and Order STM in Monolingual Children Learning a Second Language

Language learning depends not only on verbal STM but also on knowledge of phonological representations stored in long-term memory (LTM; Gathercole, 1995; Gathercole & Baddeley, 1989; Gathercole, et al., 1992; Gupta, 2003). The results from the analyses above suggest that memory for serial order can be a successful predictor of subsequent vocabulary learning in bilingual children, whereas in 7 to 10 year old ML children with limited exposure to a second language both item and order STM were related to later vocabulary knowledge. To examine whether memory for serial order predicts vocabulary acquisition in a foreign language with little or no extant vocabulary knowledge, monolingual English children learning French as a second language were examined.

As with the monolingual German children described in the previous section, the ML English children in the present study were exposed to a second language through some activities and instructions conducted in school. However, the two samples differ in several ways: First, the English monolingual group was learning French and the monolingual German group was learning English, with English and German being arguably more similar in vocabulary for early acquired words. Second, the monolingual English group was not exposed to their second language outside of the school environment whereas the German monolingual group was exposed more regularly to their second language in literature and in the media (i.e. English is becoming a more “fashionable” language in Vienna and hence more often used, but French is not commonly used in Sussex).

The aim of the analysis in this section was to further investigate the relationship between item and order STM and foreign vocabulary acquisition in a group of monolingual English speaking children who are learning French but have a relatively low level of proficiency in the foreign language. This makes the experimental group more similar to children studied by Masoura and Gathercole (1999).

Masoura and Gathercole (1999) investigated links between children´s phonological memory skills, as assessed by nonword repetition accuracy, and their knowledge of vocabulary in both native (Greek) and foreign (English) languages. Phonological memory skills and vocabulary knowledge were assessed in both languages. Knowledge of foreign but not of native vocabulary was associated with nonword repetition independently of age and non-verbal IQ. This relationship was independent of more general factors such as chronological age, nonverbal ability and the length of time spent studying the foreign language. The authors suggested that children´s learning of foreign vocabulary may be particularly highly dependent upon temporary phonological memory, in contrast to native vocabulary acquisition, due to the greater unfamiliarity of foreign words. From Masoura and Gathercole´s (1999) study we could expect that the children in the study reported in this section should show a higher correlation with verbal STM and their second language French than with English. Similar results were shown earlier in this chapter: Order STM was correlated to vocabulary in the less dominant (L2) language of dominant BL children (see Section 2.2.2. in this chapter). In ML German children item STM was stronger correlated to vocabulary knowledge at Time 2 (see Section 2.2.4. in this chapter). If the ML English children in this sample are somewhat related to the ML German children in terms of their knowledge of a second language, similar results are expected, i.e. item STM will be higher related to native language acquisition (English). In addition, from what is known about second language learning, it can be expected that order STM might be more highly related to vocabulary knowledge in their second language (French).

The aim of this section is to determine the extent to which item and order STM correlate with vocabulary knowledge in ML children learning a second language.

3.1. Methods

3.1.1. Participants

Twenty-eight monolingual English speaking children were recruited: Eleven from Year two (5 girls and 7 boys; mean age: 7.90 years; range: 7.10-8.10), ten from Year three (4 girls and 7 boys, mean age: 8.97; range: 8.01-9.09), and eight children from Year four (5 girls and 3 boys, mean age: 9.82; range: 9.11-10.10).

All students were learning French in a playful and fun way from the beginning of school in England (from age 5). The children had French classes every three weeks lasting approximately three hours.

The English ML group was only tested once, at the end of the school year.

3.1.2. Materials and Procedure

The same materials and procedure used in Section 1 were used with additional tests of French vocabulary: French active (picture naming) and passive vocabulary (Echelle de Vocabulaire en Images Peabody, EVIP, L. M. Dunn, Thériault-Whalen, & Dunn, 1993 - the French adaptation of PPVT and BPVS) tests were conducted and the item and order STM task were translated into French, matched precisely to the English task (for more details see Appendix A5).

The children took part in two sessions one week apart at the end of the school year only. The first session involved testing vocabulary knowledge and memory in English (English active and passive vocabulary, item and order STM tasks) and the second session testing in French (French active and passive vocabulary, item and order STM tasks). Unfortunately, the French order task had to be abandoned as the children did not know the animal names in French and would have processed the words as nonwords.

In addition (as argued in Analysis 2, 3, and 4, in Section 1 of this chapter, see Sections 8.2.2., 8.2.3., and 8.2.4.) it has been found that with ML children over 6 years of age, vocabulary knowledge became the dominant predictor in language development (Gathercole, et al., 1992; Majerus, Poncelet, Greffe, et al., 2006). Unfortunately it was only possible to visit the sample of ML English children learning French once, at the end of the school year and only active and passive vocabulary scores from one time point could be collected.

3.2. Results

Descriptive statistics are shown in Table 10.

Tasks	Percentage Correct (Standard Deviation)
Passive English vocabulary knowledge (BPVS 2)	56.68 (9.04)
Passive French vocabulary knowledge (EVIP)	8.36 (3.41)
Picture naming English	92.56 (3.00)
Picture naming French	9.02 (8.07)
Item STM English	71.29 (13.58)
Item STM French	66.98 (10.34)
Order STM English	41.86 (7.42)

Table 10: Descriptive statistics for English ML children learning French as a second language

As in Analysis 2, 3, and 4 (see 2.2.2., 2.2.3., and 2.2.4. in Part 1 of this chapter), partial correlations were calculated[33] in order to examine the relationship between vocabulary knowledge and item and order STM. The first set of partial correlations (r^{par1}) controlled for residual age effects and nonverbal

[33] Like in Sections 2.2.2., 2.2.3, and 2.2.4. in this chapter, conducting multiple regression analysis was not sensible due to the relatively small group size (N=28).

IQ. The next set of partial correlations additionally controlled for active English and French vocabulary knowledge (r^{par2}). Results are shown in Table 11.

The predicted correlation between serial order STM in English and French vocabulary scores was not observed (r=.152). Interestingly significant correlations were observed for the English ML children between English (L1) passive vocabulary knowledge and English order STM (r=.490, p=.009) and this correlation even remained marginally significant after taking existent active vocabulary in English and French into account (r=.374, p=.055). No significant correlations were found between English and French item STM and English passive vocabulary. None of the predictor tasks correlated significantly with French passive vocabulary. The later finding is most likely due to floor effects in French vocabulary knowledge of the English ML children (see Table 10 for descriptive statistics).

Only English active vocabulary correlated significantly with English passive vocabulary (r=.468, p=.01), but neither English nor French active vocabulary correlated significantly with French passive vocabulary. Again, these findings are likely due to floor effects in French vocabulary knowledge of the English ML children.

	English Passive Vocabulary		**French Passive Vocabulary**	
	r^{par1}	r^{par2}	r^{par1}	r^{par2}
Item STM French	-.131	-.037	.071	.196
Item STM English	.288	.175	.085	-.103
Order STM English	**.490* (p=.009)**	**.374 (p=.055)**	.152	.017
English Active Vocabulary	**.468* (p=.01)**		.172	
French Active Vocabulary	.001		-.069	

Table 11: Partial correlation between passive L1 (English) and L2 (French) vocabulary knowledge and the different predictor tasks for English ML children; *p<.05, **p<.001

3.3. Interim Discussion

Significant correlations were found only between English order STM and English passive vocabulary which remained (marginally) significant even after taking existent vocabulary knowledge into account. This finding is in line with previous research that found order STM to correlate higher with vocabulary skills in monolingual French speaking children compared to item STM (Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006).

No significant correlation was found between either serial order STM or item STM and foreign vocabulary acquisition in monolingual English children learning French. This is not in line with the finding by Masoura and Gathercole (1999). However, note that the children showed floor effects on French vocabulary learning which is also reflected in the lack of correlation between active and passive French knowledge. Hence this group should rather be considered as a relatively pure monolingual group which then would not make them strictly comparable to the group tested by Masoura and Gathercole, as their participants were exposed to L2 learning for up to 3 years, and could be considered more fully bilingual in terms of L2 knowledge than the group tested in this study.

It can be concluded that (at least in this sample of English ML children learning French) verbal STM, i.e. both item and order STM, does not seem to have a strong correlation with (very) early L2 vocabulary acquisition. It could be argued that the sample was too old to pick up correlations in verbal STM and rather depended more on existing vocabulary knowledge in L2 (as found by Gathercole, et al., 1992). However, this argument is hard to sustain as the children had very low vocabulary and hence pressure on learning new words should have been high in the French language class. Yet, contrary to this argument, the children were learning L2 in a very playful way and the focus of the class was rather a fun introduction to the French language than drilling children to learn new vocabulary. Hence there was no pressure put on them to learn new French words.

To sum up, the findings indicate that English order STM is related to native vocabulary learning in ML English speaking 7 to 10 year old children. Neither item nor order STM seems to be related to very early stages of second language acquisition.

4. Part 3: Item and Order STM Differences in Bilingual and Monolingual Children

This final section aims to explore differences in item and order STM between BL and ML children by directly comparing ML and BL performances in item and order STM tasks. The data of participants who also took part in Sections 1 and 2 were reanalysed.

Some research has suggested that BL children might outperform ML children in STM tasks (Feng, et al., 2009; Yang, Yang, Ceci, & Wang, 2005) even though this finding has been challenged (Kaushanskaya, Blumenfeld, & Marian, 2011; Namazi & Tordardottir, 2010). However, most research focuses on memory span tests but none has yet distinguished between verbal item and order STM tasks. Most importantly it has previously been argued that in immediate serial recall high frequency words generally lead to superior performance (see e.g. Hulme, et al., 1991; Poirier & Saint-Aubin, 1996). The argument here is that people are better able to interpret the traces of high-frequency words because they have richer associations in long-term memory, or phonological representations that are easier to access in lexical memory. As pointed out before (see Chapter 1, Section 4) this could automatically lead to bilinguals showing better serial order performance, especially if they know two similar languages such as English and German (both Germanic languages) as similar words might result in richer associations not only between words but also between languages. This is the case in the BL children in this chapter.

In addition, BL children might use their order STM more often than ML children, i.e. they learn and use two different sets of vocabulary and hence different phonological serial order within words (i.e. “chien”, “dog”, “Hund” etc), different sets of grammatical rules, i.e. order of words within a sentence. Monolingual children on the other hand are only acquiring one set of language knowledge and hence might not get to use their order STM as often as BL children.

The opposite might be true for item STM. As ML children only use one language, they are more often exposed to the phonology of this one language while BL children have to share the time of exposure between languages. This has been found by Messer, Jan and Mayo (2010) who investigated nonword recall and its relationship with vocabulary in ML and BL preschoolers. Children in their study had to recall nonwords with high versus low phonotactic probability in Dutch and Turkish. Superior recall of nonwords with high phonotactic probability compared with nonwords with low phonotactic probability was found. The authors claim this indicates that phonotactic knowledge was supportive for verbal short-term recall in both languages and conclude that the extent of this support depended on prior experiences with the language: Monolingual Dutch children outperformed Turkish-Dutch children on a nonword recall test in Dutch, but the BL children showed an advantage in their native language Turkish compared with their Dutch peers.

In order to ensure that any differences between bilingual children and monolingual children in their performance across tasks are not the result of additional instruction or educational demands for the bilingual group, the control children were selected from monolingual schools were a second language is taught but for no longer than three hours per week. Thus, any differences between the bilingual and monolingual children that are observed are likely not to be due to exposure to learning a second language but should depend on whether or not children are immersed in a fully bilingual schooling environment and speaking both languages fluently.

It is expected that BL children will outperform ML children in the serial order STM task but ML children might outperform BL children in the STM for item identity task.

4.1. Methods

4.1.1. Participants

Data from participants recruited for Section 1 and Section 2 in this chapter were revisited. In total, data of 85 bilingual children, 36 German monolingual children and 31 English monolingual children were analysed.

4.2. Results

In order to determine whether bilingual children were generally better at memory tasks than monolingual children, the performance on item and order STM tasks between groups of children (BL, English ML and German ML) was compared. To do this, an average score for performance in the item and order tasks for the bilingual children (English task score plus German task score divided by two) was computed to be able to compare it to both ML English and German children.

A mixed 3 x 3 x 2 ANOVA with Year (school year two, three and four) and group (ML German, ML English and BL) as between participant factors and task (item and order STM) as within participant factors was conducted. Covariates were gender and average passive vocabulary score in the native language. No significant main effects were found.

A significant task by group interaction was found $F(2,138)=9.081$, $p<0.001$ with bilinguals (raw order mean=20.06, SE=0.439) outperforming both German ML (raw order mean=18.34, SE=0.771; p=.03) and English ML (raw order mean=17.31, SE=0.765; p=0.01) in the order STM task. However, the English ML (raw item mean=29.39, SE=0.865) outperformed the ML German (raw item mean=27.01, SE=0.873; p=.03) and BL children (raw item mean=27.82, SE=0.497; p=.04) on the item STM task.

4.3. Interim Discussion

The hypothesis that BLs outperform MLs in order STM and MLs outperform BLs in item STM was partially supported. Bilingual children performed significantly better than English monolingual children in the order STM task. English ML children outperformed BL children in the item STM task. BL and ML German children showed no differences in the German tasks. This suggests that the German language itself might enhance order STM skills, perhaps because German allows more flexible sentence structures than English, as well as compound nouns. Another reason for better BL performance in English but not in German order STM might lie in the language competency of the monolingual English and German children that took part in this study. The ML German children received playful English lessons once a week compared to the ML English children who learned French as their second language once every three weeks. This difference might be enough to strengthen the order memory of the German ML children compared to the ML English children. No differences were found between German ML and BL children in German order memory. In the order task BL children outperformed English ML children which shows that BL children are better at serial order STM. Although the differences between BL and ML English children in order STM may be due to a difference in general cognitive ability between groups[34], the finding that the ML English group is better than the BL group on the item STM task mitigates against this explanation.

5. Discussion

The key aims of the present study were to clarify the role of item and order STM in native language acquisition and second language learning. It was found that in German/English BL children, English order STM predicted English

[34] See Appendix C8 for more details on IQ differences.

vocabulary at the end of the school year. This finding is in line with previous research that found that order STM is an important predictor of vocabulary knowledge (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Majerus, Poncelet, et al., 2008). However, the finding was not consistent, as German vocabulary at the end of the school year could only be predicted with existent vocabulary knowledge. It was argued that this pattern of results may have emerged as English was the less dominant language in the BL children who were growing up in a German speaking environment.

As pointed out by Gathercole, Willis, Emslie and Baddeley (1992), phonological STM (as measured with nonword repetition), or more specifically order STM (as found by Majerus, Poncelet, Greffe, et al., 2006), might only be a better predictor of vocabulary growth in children when high pressure is put on vocabulary gain. Once children´s vocabulary expands, they might be more able to make use of analogies with existing vocabulary items to learn the phonological forms of new words, thus relieving the short-term phonological memory load involved in acquiring new words (see Gathercole, et al., 1991). This could indicate that the BL children in our sample had acquired enough German vocabulary so that verbal STM was no longer of a good predictor while in English the children were still acquiring new words with the help of phonological STM. The claim that order STM is only a better predictor of vocabulary growth when high pressure is put on vocabulary gain was also supported by findings in the subgroup analysis of BL children: Order STM was significantly correlated only to the less dominant language, i.e. English order STM correlated with English vocabulary in German dominant children and German order STM correlated with German vocabulary in English dominant children, while for the native bilingual children only existent vocabulary in a given language correlated with vocabulary at the end of the school year (English vocabulary Time 1 with English vocabulary Time 2, and German vocabulary Time 1 with German vocabulary Time 2). In both languages of the high proficient native bilingual children and the high proficient language of the non-dominant bilingual children order STM did not correlate with vocabulary acquisition. Further support also came from the analysis of BL subgroups per school year: English order STM was significantly correlated to English vocabulary in the end of the school year only in BL children in Year 2 (and marginally Year 3) but not in the oldest group of BL children in Year 4. This finding indicates that younger children compared to older children might have used verbal order STM more to learn English while older children might have used different strategies. As the learner becomes more familiar with the phonology of the second language, it may be that semantic and conceptual learning take over the language learning process (see e.g., Morra & Camba, 2009).

In ML German speaking children it was found that item STM (and not order STM) significantly correlated with German vocabulary knowledge at the end of the school year. Phonological STM was also a significant predictor of nonword learning in a group of Italian ML children (Morra & Camba, 2009). In this study only real words of different length and frequency were used which led to the question whether item and order STM might be important for learning of different word types, possibly related to the language learned itself. It was argued that German has much longer words than English (see Section 2.2.1.2. this chapter for more details) hence it could be concluded from Morra and Camba´s study (2009) that for German phonological sensitivity, i.e. item STM, might be more important.

Alternatively it was argued that the German language itself might promote phonological segmentation processes (especially once children go to school and start to learn how to read and write) as it is a more phonetically accurate language (in terms of grapheme-phoneme-correspondence regularity) compared to English, which is a highly inconsistent language in terms of phonology to orthography mapping[35]. As the children were already school aged, frequently exposed to written language this might have influenced their performance. However, it still leaves the question unanswered why the German

[35] For example in German there are 5 vowel letters and 5 vowels sounds, but in English there are 5 vowel letters but depending on the accent one can find between 11 and 20 vowel sounds (see e.g., 2005; Deterding, 1997; Watt & Tillotson, 2001).

dominant BL children did not show similar results. This might be due to the fact that they not only speak one language, but in addition to German also speak English fluently and hence hold a different vocabulary pool compared to the ML German children. This could possibly lead them to use different learning strategies which might make verbal STM in the BL group not as important.

In order to further understand the relationship of item and order verbal STM a group of ML children learning French at an early stage was examined. As pointed out by Gathercole, Willies, Emslie, et al. (1992) in the early stages of the acquisition of a second language, the phonological sequences in the new vocabulary will not be familiar, in the sense that they will be represented in other phonological forms available within the learner's lexicon. In this situation, the use of existing lexical knowledge to support the temporary memory representation of new words would be expected to be minimized, thus promoting the need of phonological memory skills for long-term phonological learning. As Gathercole (2006) found highly significant links between children's phonological memory skills (assessed by nonword repetition accuracy) and their knowledge of vocabulary in both native and foreign languages, it was expected that the ML children learning French in the given sample would show significant correlations between their STM skills and their foreign knowledge of vocabulary. This was not confirmed. No correlations of item or order STM and L2 passive vocabulary knowledge were found. The non-significant result in L2 in this sample might indicate that neither item nor order STM are particularly important to very early stages of second language acquisition. Note that the children in this sample showed floor effects in vocabulary measures of French and hence can be considered early beginners of learning French. English order STM was correlated to English (L1) vocabulary knowledge even after taking into account nonverbal IQ and active vocabulary knowledge. This is similar to a finding in younger ML children who were purely French ML speaking (see Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, et al., 2006). Item STM but not order STM was related to vocabulary knowledge in ML German children. The difference between the samples is that, even though they are both monolingual children, the German ML group was more consistently exposed to a second language, English. The German ML children went to a school where BL children were also taught and hence being bilingual was promoted on a daily basis. Note that German is more similar in phonological structure to English than French is (the language that the English ML children were learning). Thorn and Gathercole (1999) point out that in the early stages of language acquisition it seems likely that languages whose phonological structure is very similar to the individual's native language will be more readily represented within the network than those whose phonological structure is quite different. This could have enhanced the effect of item STM in the German ML children. Unfortunately it was not possible to test the ML children in English as it would have been too time intensive. Future research should look into this further.

In a final analysis BL and ML children were directly compared in their performance on item and order STM tasks. BL children outperformed ML English children in order STM, but not German ML children. Again, this could be explained by the fact that either German is a more flexible language than English and hence enhances order STM in itself or alternatively the ML German children might have been more exposed to a second language (English), which might have enhanced their order STM skills. On the other hand, ML English children outperformed BL children on the item STM task, while German ML and BL children did not show significant differences. This finding was explained by the language environment: German ML and BL children lived in a German speaking environment and hence both were exposed to German phonology on a daily basis. Only the English ML children lived in an English speaking environment and hence will most likely be more exposed to English phonology than the BL children. Similar results were found by Messer et al. (2010) where ML Dutch children outperformed Turkish-Dutch children on a nonword recall test in Dutch, and in word learning studies with monolingual children at preschool age that demonstrated superior learning of nonwords with high phonotactic probability compared with nonwords with low phonotactic probability (Storkel, 2001, 2003).

Taken together, the findings extend previous results in bilingual and monolingual children from other studies (e.g., Gathercole & Baddeley, 1989; Leclercq & Majerus, 2010; Service, 1992). They suggest that order STM is the most dominant measure relating to English vocabulary knowledge as found in ML English children and BL children. Some evidence was provided that this is especially true when pressure is put on learning new vocabulary, i.e. in the less dominant language of BL children who had to study in both languages, especially in the beginning of primary school (Year 2). Item STM was related to vocabulary knowledge in German ML children. Reasons for these findings are discussed above. BL children performed significantly better in order STM tasks compared to English ML children and English ML outperformed BL children on the item STM task.

Chapter 5: Item and Order Short Term Memory and New Word Learning in Monolingual Adults

1. Introduction

Only few studies to date have investigated vocabulary learning in monolingual adults while taking into account the apparent differentiation between item and order STM. Compared to studies with bilingual speakers, where order STM appears to be a stronger predictor of vocabulary acquisition than item STM (Majerus, Belayachi, et al., 2008; Majerus, Poncelet, et al., 2008; see Chapter 4), studies with monolingual speakers show inconsistent results: In French ML adults performance on a serial order reconstruction task predicted performance on a paired associate word-nonword learning task where nonwords followed native-language-like (French) phonotactic rules (Majerus, Poncelet, Elsen, et al., 2006). All other studies with MLs investigating item and order STM and vocabulary knowledge were conducted with children: In 4 and 6 year old French speaking monolingual children it was also order STM that predicted native language learning but not item STM (Majerus, Poncelet, Greffe, et al., 2006). For 5 year old French monolingual children on the other hand, item STM predicted native vocabulary development but not order. A longitudinal follow up of the same children showed that order STM remained the only significant predictor of native vocabulary acquisition (Leclercq & Majerus, 2010). Data in Chapter 4, Section 2.2.4., showed that item STM correlated with native vocabulary acquisition in ML German speaking 7 to 10 year old children but in ML English children in the same age range order STM correlated highly with native vocabulary acquisition (see Chapter 4, Section 3).

The experiment presented in this chapter intends to help clarify two main questions: The first aim is to investigate the extent to which item and order STM processes relate to new word learning in ML English adults. The second is to determine to what extent the item and order tasks used in previous studies as well as in this thesis indeed measure similar processes by using intercorrelational analysis.

In **Part 1** of this chapter, correlations between new vocabulary learning, and item and order STM in ML English adults were calculated in order to further investigate the relation of STM to native-vocabulary type learning. The same verbal STM tasks as performed by the children in Chapter 4 were adapted for English ML adults. A new-word learning task used was designed to measure native-like new word learning, e.g. to mimic as closely as possible the processes involved in native vocabulary acquisition. In addition it compared native-language (L1) phonetic-like new word learning to learning new words based on a new, foreign language (L2). This procedure might be able to uncover possible different influences of verbal item and order STM on the acquisition of new words in (a) ones native language and (b) a foreign language – as there is evidence that first and second languages (L1 and L2) are processed differently in the brain depending on the proficiency and the age of acquisition of L2 (Eilola, Havelka, & Sharma, 2007; Hahne, 2001; Perani, et al., 1998). This study aims to fill the gap in the literature by investigating item and order STM correlations to native-like new word learning in ML English adults.

In **Part 2**, an experiment is described in which a subgroup of participants were administered the order and item recognition tasks previously used in Chapter 2 (EEG) and Chapter 3 (TMS) in this thesis. The purpose was to determine intercorrelations between the different item and order tasks used in those two experiments in order to help clarify to what extent the item and order tasks used in previous studies as well as in this thesis indeed measure similar processes. Previously, studies investigating item and order STM have used various tasks to measure these types of phonological STM. However, no study has yet investigated to what extent the tasks are measuring item STM and order STM distinctly.

2. Part 1: Investigating the Relationship between New Word Learning, Item and Order STM in ML Adults

2.1. Introduction

Previous research exploring the relationship between item and order STM and new vocabulary learning in monolingual adults used word-nonword paired learning tasks (Majerus, Poncelet, Elsen, et al., 2006). However, this process involves combining an already known word in one's vocabulary store with a new sound-pattern and is hence more akin to the process of second-language learning than that of native-language learning. It is important to point out that in children the process of learning new words usually involves pairing new sounds with new objects. Hence, the language-learning task used in this study was designed to be more naturalistic by involving new objects (i.e. a non-existing imaginary figure – see this chapter, Section 2.2.2. for more details) and combining them with acoustic presentation of new words. The aim was to determine the relationship between item and order STM and performance on a task that provides a closer approximation to the cognitive processes involved in new-word learning in the native tongue.

The first hypothesis that will be tested is that in ML English speaking adults, performance on order STM tasks should be more strongly correlated to vocabulary acquisition than performance on item STM tasks. This hypothesis was based on a finding with ML English children in Chapter 4 (see Section 2.2.4.) as well as previous studies with ML speakers (see Chapter 1, Section 4 for a review).

Previous studies used verbal stimuli that were either based on native-language-like phonetic sound patterns (Majerus, Poncelet, Elsen, et al., 2006) or on non-native language like phonetic sound patterns (i.e., Service, 1989) but no one has yet compared these two sound patterns (L1 and L2) in one study. As pointed out in the introduction of Chapter 4, evidence suggests that existing vocabulary retrieved from LTM can also influence vocabulary acquisition

(Masoura & Gathercole, 2005). Consider for example, how knowledge of a native language might influence learning of a second language. If the two languages share similar lexical forms (i.e. word forms that differ only in inflection but not in core meaning) such as cognate words (for example 'fish' in English and German or 'rose' in English and French), then extant knowledge of these forms can be generalized to learn a new form in a second language. However, note that it is not always safe to assume that what seems to be a cognate word is one (e.g. false cognates like 'room' in English and Dutch[36]). If, during the learning of new word forms, people use their verbal STM to draw on knowledge of extant lexical forms in LTM to learn new word forms, then the acquisition of foreign vocabulary may make different demands on component processes in verbal STM compared with the acquisition of native vocabulary. If this is the case we could expect that it will be easier for English monolingual speakers to learn new words based on English phonological rules, compared to learning new words based on a foreign language, such as Czech, a Slavic language, which does not have many phonological similarities to English, a West-Germanic language.

A number of component processes might be involved in new word learning, including encoding of item identity information, rehearsal and maintenance of item identity. It is an open question whether these component memory processes are used similarly during native and non-native language acquisition or if the demands of foreign vocabulary acquisition require these processes to be engaged in different ways. The relative contribution of the two types of STM may also depend on when a second language is learned, i.e. if one learns two languages simultaneously from birth or starts learning a second language later – and even then it might depend on the age. Therefore, a second aim of this study was to devise a simulated word-learning task, comparing learning new words obeying the phonotactic constraints of L1 to learning new words based on a new foreign language, L2. Such a procedure might be able to uncover possible different influences of verbal item and order STM on the acquisition of new words in (a) one`s native language and (b) a foreign language – as there is evidence that first and second languages (L1 and L2) are processed differently

[36] The Dutch word ‚room' means ‚cream'.

in the brain depending on the proficiency and the age of acquisition of L2 (Eilola, et al., 2007; Hahne, 2001; Perani, et al., 1998).

From previous studies we know that order STM predicted L2 learning in BL English/German children in English (see Chapter 4, Section 2.2.2.). Order STM also correlated more highly with native L1 learning in ML English children (Chapter 4, Section 3). In addition we know that in BL English adults learning French, order STM predicted French (L2) based nonword-word pair learning (Majerus, Poncelet, et al., 2008). In ML French adults, order STM predicted word-non-word paired learning of L1 (French) based nonwords (Majerus, Poncelet, Elsen, et al., 2006). On the other hand it was item STM and marginally order STM that predicted vocabulary learning in ML German children (see Chapter 4, Section 2.2.4.. However, results from the study with children in Chapter 4 suggest that language influences the relationship of item and order STM with vocabulary differently. So far, previous studies conducted with English suggest that order STM might be a stronger predictor for vocabulary learning in this language. It is hypothesized that STM for serial order will be more highly correlated with new word forms following in L1-phonetic patterns (English) and L2-phonetic patterns (Czech), compared to STM for item identity.

2.2. Methods

2.2.1. Participants

32 monolingual native English speakers (18 female) were recruited from the University community. Age ranged from 18 to 24 years, with a mean of 20.53 years (SD = 1.39 years). All participants gave their written informed consent prior to their inclusion in the study (see Appendix D1 for details) and were paid for participation. The study was approved by the Ethics Committee of the School of Psychology of the University of Sussex.

2.2.2. Materials

Order Reconstruction Task

This task was based on the one used in the longitudinal children´s study (Chapter 4). It was designed to maximize order STM skills and minimize item STM demands. It consisted of the auditory presentation of lists of increasing length containing highly familiar animal names, identical to the ones in Chapter 4. The main difference between the version of the task used in the present experiment and the one described in Chapter 4 was the list length, and hence task difficulty: Instead of 3-7 animals presented to children, lists contained 4 to 9 monosyllabic animal names (dog, mouse, fish, cat, whale, sheep, hen, bear, and cow). Participants were asked to remember the animal names in their correct order. After the auditory presentation of the list of animal names, the participant saw pictures of the animals on the computer screen. Participants had to click on the pictures in the same order that the names had appeared. The task is also similar to the serial order reconstruction task used by Majerus, Poncelet, Elsen and Van der Linden (2006) and to the serial order reconstruction "animal task" used in a developmental study by Klingebiel, Weekes and Majerus (2009). Serial order reconstruction tasks as opposed to serial order recall tasks have been shown to be relatively independent of language factors such as phonology effects but to tap into language independent order short-term memory processes (see e.g., Thorn, et al., 2002). For analysis two scores were calculated: the number of sequences correctly reconstructed out of a total of 40 item lists (one point for each sequence of animals correctly reconstructed) and the correct number of animal names remembered out of a total of 264 animal names (one point for each animal remembered in its correct position). Preliminary analysis showed that these measures correlated very highly ($r=.934$, $p<.001$) even after accounting for nonverbal IQ, and active and passive vocabulary knowledge ($r=.927$, $p<.001$). The measure of all correctly recalled animal names is reported in the following analyses.

Item Rhyme Probe Task

This task was based on the one used in the longitudinal children´s study (Chapter 4). It was designed to maximize item STM skills and minimize order STM demands. Again, the main difference between the version of the task used in the present study and the one described in Chapter 4, Section 2.1., was that list length was longer, to increase task difficulty for adults. Instead of the 3 to 7 words presented to children, lists of 4 to 9 words were created. Participants were instructed that they will hear a list of words, followed by a probe word and they were then asked to judge whether the probe word rhymed with one of the words in the list or not. After hearing the probe word, the participants had to press YES if the word after the beep rhymed with one of the words heard before or NO if the item had not rhymed with any of the words before. This task was adapted from the item STM task developed by Majerus, Poncelet, Elsen, et al. (2006) and is similar to the rhyme probe recognition task "rhyme game" used in a developmental study by Klingebiel, Weekes and Majerus (2009). Rhyme probe recognition tasks are thought to tap into language dependent item information short-term memory processes (Majerus, Poncelet, et al., 2008). The proportion of correct recognition trials over all forty experimental trials was calculated for each participant.

English Passive and Active Vocabulary Knowledge

In order to control for the influence of lexico-semantic knowledge on STM performance, standardized vocabulary tasks were administered:

Receptive vocabulary knowledge was assessed using the British Picture Vocabulary Scale (BPVS-II; L. M. Dunn, Whetton, et al., 1997). It contains items ordered as a function of difficulty and age of acquisition. The final score is calculated as the rank of the final item reached minus the number of erroneous responses (stop criterion: six erroneous responses on the last eight trials). The number of correct matching responses (percentage known correctly) was also determined.

Productive vocabulary was assessed using a picture naming task (see also Francis, 1999; Grosjean, 1989). The pictures were a subset of the Snodgrass and Vanderwart(1980) pictures including 38 pictures sampling equally through high and low lexical frequency ranges. The pictures were presented for naming in English using E-prime 2.0 (Psychology Software Tools Inc., Pittsburgh, PA) on different occasions during the testing sessions (see below for details on order of presentation). The English picture naming task was merely a control condition as we expected only very few errors in this task for native English speaking participants. The number of correct naming responses (percentage named correctly) was determined.

Estimate of General Reasoning Abilities

The Test of “g”: Culture Fair (Scale 2, Form A) by Cattell and Cattell (1957) was administered in order to obtain an estimate of nonverbal reasoning abilities to control for general intellectual functioning and abilities.[37]

Paired Associate Picture-Nonword Learning Task

A novel paired associate picture-nonword learning task was constructed. The aim of this task was to tap into the fundamental processes involved in learning a new word in a native language (i.e. native language learning) as opposed to learning of new words in a second, foreign language (i.e. second language learning). As in Gupta (2003), textual presentation of word-form pairs was avoided and instead parings consisting of an auditorily presented novel word form with a visual image depicting its referent were used. The referent was

[37] This test was used as it shows reliable screening results and as it was readily available at the time of testing.

a novel object, so that the word form had to be linked to previously unnamed semantics rather than to already known semantics. The novel objects were “creatures from other planets” (images of aliens which were acquired from various internet sources and resized to the same pixel dimensions). The advantage of these stimuli is that they have little resemblance to known objects, and hence are less likely to evoke pre-existing names. The participant`s task was to learn the names of the pictured objects, so that they could subsequently produce the names when cued with the pictures.

In total, 12 picture-nonword pairs were created: Six nonwords were native-like and six were foreign-like. Native-like nonwords were created by using the bisyllabic CVC-CVC-structured English words “signal”, “dungeon”, “pistol”, “quarter”, “between”, and “compass” and exchanging the two syllables, creating the following nonwords:/nʌl –‘sɪg /, /dʒən –‘dʌn /, /təl –‘pɪs /, /tər –‘kwɔr /, /win-bɪ’t/, and /pəs-’kʌm /. Non-native like nonwords were created by using the bisyllabic CVC-CVC-structured Czech words “celkem” (altogether), “končit“ (to finish), “číšník“ (waiter), “kašlat“ (to cough), “kostel“ (church), and “nástup“ (entry) and exchanging the two syllables, creating the following nonwords: /kɛm-tzɛl/, /tʃɪt-kɔn/, /nik-tʃiʃ/, /lʌt-kʌʃ/, tel-kɔs/, and /tʊp-nʌs/. In order to avoid floor effects, only diphones that were frequent in English phonology were selected when creating the nonwords.

Pictures were randomly paired with the nonwords. All nonwords were recorded by a fluent English-Czech speaker and presented verbally via E-Prime to the participant, each one paired with an alien picture. The picture / nonword pairs were presented in two blocks, each comprising three Czech and three English picture-nonword pairs (a total of 6 pairs per block).

Each block consisted of two steps: Three picture-nonword pairs were presented via E-Prime on a computer screen to the participant, one at a time. After each pair a star appeared on the screen and the participant was asked to repeat the alien’s name. After the presentation of three picture-nonword pairs, the participant was presented with each of the three alien pictures, again one at a time, and requested to repeat the corresponding nonword. See Figure 47 for an example of one block of the paired associate picture-nonword learning task.

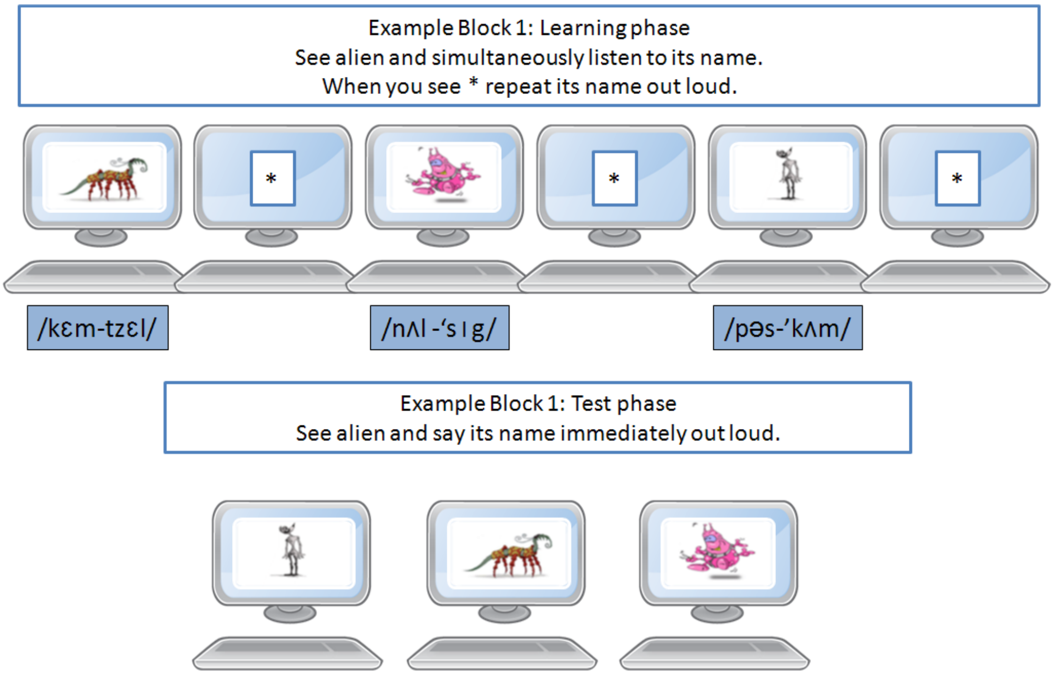

Figure 46: Example of one block of the new-word learning task for ML adults

No feedback was given. This procedure was repeated four times with the same 3 aliens in random order. Then, the second set of three picture-nonword pairs was presented in the same way[38]. Instructions to the participants were as follows: “You will hear sets of three unfamiliar words, each one combined with a picture of a creature from another planet. After each word-picture pair, a cross will appear on the screen. When the cross appears, repeat the word you just heard. Try to learn the name of this alien. After the set of three pairs has been presented, the pictures of the aliens will appear on the screen and you will be asked to name the aliens.”

A break including a filler task, the Test of “g” to measure general non-verbal reasoning skills which took approximately 10 minutes was given to the participants. This filler task did not feature nonwords and was given to participants in between the two blocks (for details of procedure see Table 12). This procedure was chosen to ensure reasonable learning success and to avoid possible risks of confounding newly learned nonwords with nonwords from other

[38] For the complete set of stimuli please look up Appendix D2.

tasks involving nonwords. The number of items to be learned is comparable to the number used in other studies (see e.g., Gupta, 2003; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, et al., 2008)

Structure of nonword-learning task

	Stimulus	*Participant response*
1.	Nonword target 1 + Alien 1 picture	* =>Repeat nonword
2.	Nonword target 2 + Alien 2 picture	* =>Repeat nonword
3.	Nonword target 3 + Alien 3 picture	* =>Repeat nonword
4.	Cues: Alien 1 -3 pictures in random order	Name aliens
5.	[Repeat Steps 1-4 3 times, with Alien 1-3 in random order]	
6.	[Repeat Steps 1-5 4 times, with Alien 4-6 in random order]	
	BREAK – another task not including nonwords was conducted (Test of “g”)	
7.	Nonword target 7 + Alien 7 picture	* =>Repeat nonword
8.	Nonword target 8 + Alien 8 picture	* =>Repeat nonword
9.	Nonword target 9 + Alien 9 picture	* =>Repeat nonword
10.	Cues: Alien 7 -9 pictures in random order	Name aliens
11.	[Repeat Steps 1-4 3 times, with Alien 7-9 in random order]	
12.	[Repeat Steps 1-5 4 times, with Alien 10-12 in random order]	

Table 12: Structure of the paired associate picture-nonword learning task

An entirely correct response was assigned two points (one for each correctly named syllable). A response where only one of the two CVC syllables was correctly recalled was credited one point. The final score represented the total number of points for the eight cued recall trials, divided by the maximum possible score (=96).

2.2.3. Procedure and Order of Task Administration

Participants were all tested in a one-to-one setting with the experimenter. Tests were administered in two different orders as presented in Table 13, with the order rotated across participants:

Test-Set A	Test-Set B
Order reconstruction task	English productive vocabulary test
Item rhyme probe task	Nonword learning task Part B
English productive vocabulary test	Non-Verbal IQ test
English receptive vocabulary test	Nonword learning task Part A
Nonword learning task Part A	English receptive vocabulary test
Non-Verbal IQ test	Item rhyme probe task
Nonword learning task Part B	Order reconstruction task

Table 13: Order of task administration

Note that no tasks using nonwords occurred in between the two nonword-learning tasks. This was important in order for participants to learn the relevant nonwords in the nonword learning tasks without non-relevant nonwords interfering with the learning process. In addition, half of the participants started with the Nonword learning task Part A, and the other half started with the Nonword learning task Part B. All tasks were presented in a single session lasting about 90 minutes.

2.3. Results

Descriptive statistics are shown in Table 14.

Tasks	Percentage Correct (Standard Deviation)
Passive English vocabulary knowledge (BPVS 2)	86.57 (05.34)
Picture naming English	88.90 (07.19)
Item STM English	81.73 (06.74)
Order STM English	41.64 (13.52)
Non-Verbal IQ	77.72 (10.03)
New Word Learning Task (All Words)	60.87 (12.98)
New Word Learning Task (L1- phonetic based Words)	62.18 (14.50)
New Word Learning Task (L2- phonetic based Words)	58.33 (13.49)

Table 14: Descriptive statistics for English ML adults

2.3.1. Relationship between New Word Learning, Order STM and Item STM

First, correlations between item and order STM and general new word learning were calculated, followed by the investigation of differences between learning new words based on L1 and L2-phonetic patterns, and finally correlations between item STM, order STM and vocabulary knowledge and L1- and L2- phonetic-based new-word learning tasks were analysed.

Correlations between Item and Order STM Measures and New-Word Learning

Correlations and partial correlations were calculated[39] in order to examine the relationship between new word learning and item and order STM. Partial correlation controlled for active and passive vocabulary knowledge in English and nonverbal IQ.

The mean percentage correct score for the new-word learning task was 60.12% (range 33.33-82.29%). When looking at the overall new-word learning score, the verbal order reconstruction task correlated significantly (r=.372, p=.036) with general nonword learning, and the item rhyme probe task also correlated marginally (r=.347, p=.052; see Table 15). These relationships did not remain significant after partialling out active and passive vocabulary and non-verbal IQ.

	Overall New-Word Learning	
	r	**$r^{partial}$**
Item Rhyme Probe Task	.347 (p=.052)	.270
Order reconstruction Task	.372* (p=.036)	.277

Table 15: Simple and partial correlations (after control of vocabulary knowledge, non-verbal IQ, age and gender) between STM measures and new word learning

[39] As in Chapter 4, conducting multiple regression analysis was not sensible due to the relatively small group size (N=32).

Differences between Learning New Words Based on English (L1) Phonological Rules and Words Based on a Foreign Language (L2)

Correlations and partial correlations were calculated[40] in order to examine the relationship L1-phonetic based new word learning and L2-phonetic based new word learning. Partial correlations controlled for active and passive vocabulary knowledge in English and nonverbal IQ.

The mean percentage correct score of the L2-phonetic based new-word learning task was 56.45% (range=22.92 – 75.00%), mean percentage correct score of the L1-phonetic based new-word learning task was 61.91% (range=29.17 – 81.25%). Preliminary analysis showed that the two scores were correlated (r=.564, p=.001). ML adults performed similarly well in both L1- and L2-phonetic based new-word learning tasks as revealed by a paired samples t-test, t(31)=1.658, p>.05. However, the fact that the correlations are not extremely high (see Table 16 for detail), even though both types of words had to be learned in the same way, may suggest that different language learning processes are involved. Hence split analysis for the two types of words (L1 and L2) will be reported below.

	L2 New Word Learning	
	r	**$r^{partial}$**
L1 New Word Learning	.564** (p=.001)	.514** (p=.004)

Table 16: Simple and partial correlations (after control of vocabulary knowledge and non-verbal IQ) between L1 and L2 new word learning tasks (N=32)

[40] As in Chapter 4, conducting multiple regression analysis was not sensible due to the relatively small group size (N=32).

Correlations between Item and Order STM and vocabulary Measures and New-Word Learning with New Word Forms Following L1 (English) - and L2 (Czech) – Phonetic Patterns

Correlations and partial correlations were calculated in order to examine the relationship between L1-phonetic based new-word learning, L2-phonetic based new-word learning, item and order STM. Partial correlations controlled for active and passive vocabulary knowledge in English and nonverbal IQ. In addition, correlations between active and passive vocabulary measures in English and L1-phonetic based new-word learning and L2-phonetic based new-word learning were calculated as in earlier research presented in this thesis it was found that only vocabulary in a given language correlated with new-word learning in a given language (i.e. English vocabulary at Time 1 correlated with English vocabulary at Time 2, and German vocabulary at Time 1 correlated with German vocabulary at Time 2). It was expected that English vocabulary would correlate only with L1-phonetic based new word learning but not L2-phonetic based new word learning.

For L1 new-word learning, order STM correlated significantly ($r=.397$; $p=.025$), and item STM correlated marginally significantly ($r=.348$, $p=.051$). However, only order STM remained marginally significant ($r=.329$, $p=.094$) after partialling out active and passive vocabulary and non-verbal IQ. For the L2 new word learning task, none of the variables correlated significantly. See Table 17 for details.

	L1 new-word learning		L2 new-word learning	
	r	**r^{partial}**	**r**	**r^{partial}**
Item Rhyme Probe Task	.348 (p=.051)	.191	.280	.143
Order reconstruction Task	.397* (p=.025)	.329 (p=.094)	.195	.089
English Passive Vocabulary (BPVS II)	.230		.162	
English Active Vocabulary (Picture naming)	**.361* (p=.042)**		.261	

Table 17: Simple and partial correlations (after control of vocabulary knowledge, non-verbal IQ, age and gender) between STM measures and L1 and L2 new word learning in English ML adults

2.4. Part 1 - Interim Discussion

The primary aim of this study was to extend the research presented in Chapter 4 and investigate the relative contributions of item and order STM processes to new word learning in ML adults as opposed to children.

On the basis of previous studies showing that order STM has been the major predictor of new word learning in French ML children (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, et al., 2006) and French ML adults (Majerus, Poncelet, Elsen, et al., 2006) it was predicted that order STM would correlate more highly with nonword learning than item STM. Indeed it was found that the verbal order STM task significantly correlated with general nonword learning. Item STM also correlated marginally with new word learning. After partialling out existing vocabulary knowledge and non-verbal IQ none of the predictor variables remained correlated with general new word learning.

Based on Storkel´s finding (2001) that new words containing phonological sequences that are frequent relative to the phonology of the native language are learned faster than new words containing less frequent sound structures, it was hypothesized that participants would learn native-like nonwords significantly better than the non-native like ones. However, this hypothesis was not supported. No significant differences in performance between the two types of new words were found in the ML English adults. Hence it can be concluded that L1-based new words in the given task do not seem to be learned more easily than L2-based words. It was assumed that learning words based on one´s native language depends on pre-existing vocabulary stored in long term memory as shown in previous studies (Gathercole, 1995; Gathercole & Baddeley, 1989; Gathercole, et al., 1992; Gupta, 2003). Hence it was expected that learning L1-based words would be easier for English ML speakers compared to learning new words, based on L2, a foreign language. Czech-based nonwords were chosen as L2-words, as Czech is a Slavic language which has few similarities to English, a west-Germanic language. However, to avoid floor effects unknown phonemes such as ě, š, č, ř, ž, and difficult consonant clusters were avoided in building non-words. Hence it can be argued that even though the words were based on Czech, we used words which consisted of pronounceable English-like phonemes making them similar to English words. Hence, even though there is evidence that first and second or unknown languages are processed differently in the brain depending on the proficiency and the age of acquisition of the second or new language (Eilola, et al., 2007; Hahne, 2001; Perani, et al., 1998) this argument may not apply when both word-types were processed in adults as new words based on the phonemes of the participants´ mother tongue: English.

As the correlations of L1- and L2- based new-word learning with item and order STM was not extremely high, further analysis was conducted with the two language tasks separately. Results supported the prediction that STM for serial order would be more highly correlated with new word forms following L1-phonetic patterns (English), compared to STM for item identity. For L1 based new-word learning, both item and order STM tasks correlated significantly but only order remained marginally significant after accounting for existing vocabulary, non-verbal IQ, age and gender. The prediction that order STM would also correlate more highly with L2-phonetic based new words was not supported. No significant correlations were found between item and order STM and L2-based word learning. In addition, English active vocabulary knowledge only correlated with L1-based new word learning but existent English vocabulary did not correlate with L2-based new word learning[41]. This finding does suggest that the words based on Czech (L2) were indeed processed somewhat differently in ML English speakers as neither the item nor order STM task nor existent English vocabulary correlated with its test-scores significantly (unlike the L1-based nonword learning tasks that did correlate with order STM, even after controlling for existent vocabulary knowledge and non-verbal IQ).

These results are consistent with Majerus et al.´s (2006) suggestion that order STM capacities play a specific role in learning new phonological information. From the data in this sample it can be concluded that, at least in English speaking MLs, this is only the case for phonological information based on the native language but not for a foreign language. Similar results were found in ML English speaking children learning French, where order STM only correlated with L1 (English) vocabulary but not with French (L2) vocabulary which showed floor effects (refer back to Chapter 4, Section 3). It was argued, that verbal STM, i.e. both item and order STM, does not seem to have a strong correlation with (very) early L2 vocabulary acquisition. This claim was strengthened by the current finding with ML adults.

Indeed, in Majerus et al.´s (2006) study nonwords were based on participants` native language, French (L1). In a study by Majerus, Poncelet et al., 2008, with English BLs who had various levels of French proficiency, it was also order STM (and French proficiency scores) that independently predicted performance on a paired-associate word-nonword learning task with nonwords based on French (L2). Majerus et al. (2008) found that French (L2) proficiency scores and the serial order STM measure independently predicted performance on a paired-associate learning task. They suggested that their results highlight the importance of phonological knowledge and serial order STM in lexical learning. Note, that they did not investigate L1-based nonwords but that their

[41] Note that part of the discussion of results revolves around comparison of differences in correlations. These sections need to be considered with caution as statistical tests were not conducted to determine whether the differences in correlation coefficients are actually significant.

participants studied the language of the nonwords (French) and hence were (at least somewhat) familiar with the L2-phonetic sound pattern.

In the sample in this study, Czech was used as L2, a complete novel language to our participants. Here neither item nor order correlated significantly with new word learning. The results highlight that the relationship of order STM (and also item STM) to vocabulary acquisition seems to be highly language-specific. It would be interesting to see whether the order STM of the participants in this sample would start to correlate with the L2 (Czech)-based nonwords after participants started studying Czech as a second language. This would further strengthen the suggestion that order STM might be involved in new-language learning. Maybe exposure to learning a completely novel language does not yet trigger the importance of order STM as a predictor of learning, as analyzing foreign sound patterns might be more important at first. Order STM might become more important once a language has been somewhat established.

To sum up, the order reconstruction STM task correlated significantly with L1-based new word learning only, and even remained marginally significant after controlling for non-verbal IQ and existing vocabulary knowledge.

3. Part 2: Investigating Intercorrelations between the Different Item and Order Tasks Used in This Thesis

3.1. Introduction

In addition to filling a gap in the literature by investigating item and order STM correlations to native-like new word learning in ML adults, a subgroup of participants was also administered the order and item recognition tasks used in Chapter 2 (EEG) and Chapter 3 (TMS) in this thesis. These tasks were designed to reveal differences between item and order STM during their processing in the brain. In both tasks four words were presented one at a time, then two probe words appeared and the participant had to make an item or order judgment. This was done to take the opportunity to determine the extent to which different measures of item and order STM correlate with each other. Previous studies have used different types of tasks to examine item and order verbal STM, assuming across experiments that they are measuring the same underlying processes[42], and in fact, different tasks have also been used throughout this thesis (e.g. EEG-Chapter 2 and TMS-Chapter 3 using different tasks as compared to the Child-Chapter 4 and Chapter 5 with ML adults). No one has tested the extent to which different measures of item and order STM correlate with each other by looking at performance on all tasks in the same sample.

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[42] See e.g., Majerus, Poncelet, Elsen & Van der Linden, 2006; Leclercq & Majerus, 2010; Poirier & Saint-Aubin, 1996; Henson, Hartley, Burgess, Hitch &Flude, 2003; Nairne& Kelley, 2004; Jefferies, Frankish & Ralph, 2006; Mosse & Jarrold, 2008; Majerus, Leclercq, Grossmann, Billiard, Touzin et al., 2009; Majerus, Heiligenstein, et al., 2009; Baddeley, Papagno & Vallar, 1988; Trojano & Grossi, 1995; Majerus, Norris & Patterson, 2006; Majerus, Glaser, Van der Linden & Eliez, 2006; Henson, Burgess & Frith, 2000; Marshuetz, Smith, Jonides, DeGutis, & Chenevert, 2000; Majerus, Poncelet, Van der Linden, et al., 2006; Majerus, Bastin, Poncelet, Van der Linden, Salmon, Collette, et al., 2007; Majerus, D'Argembeau, et al., 2009.

The aim is to find out to what extent the different item and order tasks indeed measure similar processes.

If item and serial order STM are determined by distinct processes and capacities, then we should observe stronger correlations between tasks measuring STM for the same type of information (i.e. order reconstruction performance and order recognition performance or item rhyme probe performance and item recognition performance) than between tasks measuring distinct types of information (i.e. order reconstruction performance and item recognition performance). To test this, a series of correlations was calculated between the four tasks used in previous research as well as in this thesis: performance on the Order reconstruction task (as used in the ML adult and children´s study), order recognition task (as used in the EEG and TMS study), item rhyme probe task (as used in the ML adult and children´s study) and item recognition task (as used in the EEG and TMS study) will be compared.

3.2. Methods

3.2.1. Participants

32 English monolingual speakers who also participated in the experiment reported in Part 1 in this chapter[43].

3.2.2. Materials

In addition to the Item Rhyme Probe Task and Order Reconstruction Task (for a description see this chapter, Part 1, Section 2.2.2.; these tasks were not re-administered but only scores of the tasks were re-analysed), 21

[43] Due to a technical failure only data of 21 participants of the item recognition and order recognition task could be retrieved.

participants were also administered the tasks of the EEG and TMS study (Chapter 2 and 3). These two tasks were simply added to Test-Set A or Test-Set B (see Section 2.2.3. in this chapter) in the same session all the other tasks were tested. To remind the reader of these tasks, a brief review is given below.

Order Recognition Task

The order recognition task was identical to the one used in the EEG Chapter (see Chapter 2, Section 4.2.2. for more details) and the TMS Chapter (see Chapter 3, Section 4.3. for more details). Each trial consisted of the sequential presentation of four words in a study phase followed by a blank screen and two probe words (see Fig. 8; Chapter 2, Section 4.2.2. for details on stimulus duration and timing). Both probe words had been presented in the study phase, but not necessarily in the given order. Participants had to judge whether the probe word presented on the left of the screen had occurred before the probe word presented on the right.

Item Recognition Task

The visual rhyme probe recognition task, like the serial order recognition task, was identical to the one used in the EEG Chapter (see Chapter 2, Section 4.2.2. for more details) and the TMS Chapter (see Chapter 3, Section 4.3. for more details). Each trial consisted of the sequential presentation of four words in a study phase followed by a blank screen and two probe words (see Fig. 8; Chapter 2, Section 4.2.2. for details on stimulus duration and timing). There were two conditions: Either both probe words had been presented in the study phase or one had not been presented in the study phase. Participants had to judge whether the two probe words were identical to any of the words in the study list or if one of them was different from any in the study phase.

3.2.3. Procedure and Order of Task Administration

Participants performed the experiment as described above (see Part 1 in this chapter) and some of the participants did two additional tasks: The item and order recognition tasks. They completed these two additional tasks after they had finished the tasks of part 1. Half of the participants completed the order recognition task first, the other half the item recognition task.

3.3. Results

Descriptive statistics are shown in Table 18. Percentage correct (based on the maximum possible score for each task) was used for analysis. Level of difficulty was fairly similar across the item and order tasks, with only the order reconstruction task showing a low percentage correct compared to the other tasks.

Tasks	**Percentage Correct (Standard Deviation)**
Item rhyme probe task (N=32)	81,73 (06.74)
Item recognition task (N=21)	84,05 (11.85)
Order reconstruction task (N=32)	41.64 (13.52)
Order recognition task (N=21)	84.88 (11.36)

Table 18: Descriptive statistics for the different item and order STM measures (percentage correct)

Correlations between Verbal STM Measures

When correlating all item and order tasks, as expected the item recognition task correlated with the item rhyme probe task ($r=.525$, $p=.014$). Marginal correlations were also found between the order recognition and order reconstruction task ($r=.391$, $p=.08$). Correlations were also found between the verbal STM measures (order reconstruction and item rhyme probe; r=.387, p=.029) and visual STM measures (order recognition and item recognition; r=.689, p=.001). No correlation was found between the order recognition task and item rhyme probe task (r=.329). This was expected as these tasks were thought to measure distinct capacities, i.e. verbal item versus visual order STM. However, the visual item recognition task also correlated highly significant with the verbal order reconstruction task (r=.586, p=.005).

After controlling for nonverbal IQ and active and passive vocabulary, most correlations did not remain significant. The large reduction in the strength of the correlation between item and order STM scores suggest that much of the relationship of the performance on these two tasks is accounted for by individual differences in general non-verbal IQ and vocabulary knowledge. Interestingly, the correlation between the visual item recognition task and the verbal order reconstruction task remained significant (r=.475; p=.046). See Table 19 for details.

	Order reconstruction		**Item recognition**		**Order recognition**	
	r	$r^{partial}$	r	$r^{partial}$	r	$r^{partial}$
Item rhyme probe (N=32)	**.387* (p=.029)**	.379	**.525* (p=.014)**	.148	.329	-.385
Order reconstruction task (N=32)			**.586** (p=.005)**	**.475 (p=.046)**	**.391 (p=.08)**	-.073
Item recognition task (N=21)					**.689** (p=.001)**	.309

Table 19: Simple and partial correlations (after control of vocabulary knowledge and non-verbal IQ) between STM measures.

3.4. Part 2 - Interim Discussion

In this sub-analysis, two item (verbal item rhyme probe and visual item recognition task) and two order tasks (verbal order reconstruction and visual order recognition task) were correlated to investigate if item and serial order STM are determined by distinct processes and capacities. It was hypothesized that stronger correlations should occur between tasks measuring STM for the same type of information (i.e. order reconstruction performance and order recognition performance or item rhyme probe performance and item recognition performance) than between tasks measuring distinct types of information (i.e. order reconstruction performance and item recognition performance).

As expected, the item rhyme probe task correlated with the item recognition task more strongly than with the order reconstruction or order recognition tasks. However, the order recognition task correlated only marginally with the order reconstruction task. It is highly likely that significance could not be reached due to limited participants (N=21). As anticipated, the item rhyme probe task measured a similar component as the item recognition task and can be thought of an “item STM component”. However, it needs to be acknowledged that there is less evidence (in the current limited analysis) for the two order STM tasks measuring the same underlying processes. This is an important finding as previous studies have used both tasks alternately to explore item and order verbal STM differences, in e.g. neurological studies to investigate different neural processes of item and order STM as well as in behavioural studies trying to predict vocabulary acquisition of new and foreign vocabulary.

No correlations were found between the order recognition and item rhyme probe task as anticipated. However, somewhat surprisingly, the item recognition task and the verbal order reconstruction task correlated highly with each other, even after controlling for vocabulary knowledge and non-verbal IQ, were. This correlation between the item recognition task and order reconstruction task is likely to indicate that the item recognition task used in EEG and TMS experiments might also somewhat activate order verbal STM.

The tasks used in the EEG/TMS experiments were designed to be as closely matched in every feature possible in terms of the input and output requirements (each task involved remembering four words, and the response involved a judgment whether the two words presented had occurred in the list or not). Matching tasks in this way allows any differences in terms of ERP signals, or differences in performance post-stimulation, to be attributed to the cognitive processes on which the tasks differ- namely the requirement to remember item or order information in verbal STM. As shown in the EEG experiments (see Chapter 2) the two tasks do elicit different brain activities in ML adults and ML children and hence do seem to tap into two different processes. In both of the tasks two words appear in the probe-phase, and hence it is therefore likely that some order STM processing was also involved, even when the task was to determine whether either one of the items was on the learning list.

It was found that the item and order recognition tasks, which were also used in the EEG (Chapter 2) and TMS (Chapter 3) experiments in this thesis, correlated positively, indicating that they both measure at least partially overlapping skills. Partial analysis revealed that the principal determinants of this relationship are non-verbal IQ and existent active and passive vocabulary knowledge as the correlation did not remain significant when these other variable were partialled out. Yet, when using these tasks in fMRI and EEG studies, different processing areas in the brain were revealed indicating that even though they measure partially overlapping skills they also reflect distinct processes (see e.g., Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, et al., 2008; Chapter 2 this thesis).

Significant correlations were also observed between order reconstruction and item rhyme probe tasks, again indicating that they do depend on at least partially overlapping cognitive processes. Yet, in children it has been shown that the two tasks have differential predictor abilities, in that the order reconstruction task significantly predicted vocabulary acquisition in bilingual children and the item rhyme probe task significantly predicted vocabulary acquisition in monolingual children (see Chapter 4, Section 2.2.4.). Hence as in the item and order recognition task, even though the two tasks seem to rely on partially overlapping processes they also measure distinct features. As discussed by

Majerus, Poncelet, Elsen, et al. (2006), the association between the tasks raises the question whether both tasks measure other shared processes. They point out that it may be the case that participants use serial scanning processes to determine whether the probe word rhymes with one of the words in the list. General vocabulary knowledge and nonverbal IQ can be ruled out as mediators of this correlation. A possible explanation is that both measures reflect temporary storage capacities of phonological information (see Majerus, Poncelet, Elsen, et al., 2006). However, if both measures reflect only common mechanisms for storing phonological item information then they should also show similar correlation profiles with new word learning, which is not the case, as found in children´s data reported in this thesis (see Chapter 4, Section 2) and other studies (see Chapter 1, Section 4 onwards for reviews).

Taken together the findings of the sub-analysis point out that even though the item and order STM tasks depend to some extent on related processes, it is certainly not the case that they are identical in what they are indexing. Evidently, the cognitive processes involved in item recognition STM overlap somewhat with the ones with order reconstruction STM and it can be concluded that item and order STM are not completely independent.

4. Discussion

The present study had two aims. One was to close a gap in literature by applying a more natural learning task to 32 adult monolingual English speakers to investigate whether the item and order STM correlations with vocabulary acquisition found in children can also be obtained in adults. An additional aim was to investigate intercorrelations between the different item and order tasks to find out if the tasks measure the processes that their names imply, i.e. item STM tasks both measure item and order STM tasks both measure order STM.

In Part 1 of this chapter it was found that L1-based new word learning correlated with order STM whereas L2-based new word learning did not. The results of the correlations are in line with previous studies that found order STM to be more strongly correlated with vocabulary acquisition than item STM (see Chapter 4, Part 2, English vocabulary development in bilingual children; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Majerus, Poncelet, et al., 2008). In addition they suggest that other mechanisms than verbal item and order STM might be important for very early L2-learning.

Part 2 revealed that even though the item and order STM tasks measure somewhat related processes, it is certainly not the case that they are identical in what they are indexing. A high correlation between the visual item recognition task and the verbal order reconstruction task that remained significant after partialling out non-verbal IQ and active and passive vocabulary knowledge, suggests that the item STM task used in the TMS and EEG study (Chapters 2 and 3) also involves order STM processes.

It is important to note that the item and order recognition tasks used in this correlational analysis as well as in the TMS and EEG study (Chapters 2 and 3) were also used in previous fMRI studies by Majerus et al. (see Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006) The authors first used two different types of item STM conditions: Both were identical in terms of task procedure, i.e. four words came up one at a time and then two probe stimuli showed up where the participants had to indicate whether or not they had been in the list or not. However, the item STM tasks differed in the presentation of probe stimuli: In the first item STM task the authors called “Item_1w”, the probe stimuli consisted in the presentation of the same word twice, differing in 50% of trials from one of the target words by a single letter and phoneme. The authors pointed out that this was the “purest item condition”, given that detailed item STM representations had to be formed and to be compared to a single probe item, but presented twice in order to match the amount of visual information of the order recognition task. The other item condition called “Item_2w” was similar to the one used in this thesis (see Chapters 2, 3 and 5). It included two different items that both had to be compared to the items in the stimulus list. The authors pointed out that this form of item STM condition is more “hybrid” in the sense of combining item and order STM processes given that the probe stimulus comprised two different items and both had to be compared to the items of the stimulus list, or, put in other words, the very fact that there are two items in both item and order recognition tasks, means that participants inevitably have to process order, in that they read first one word, and then the other. This is also reflected in the significant correlation of item recognition and order reconstruction task in the correlational analysis in this chapter. In previous studies by Majerus et al. (2006; 2008), the item_2w STM condition allowed a check for any differences between the item and order conditions that might have been created by the fact that the probe condition necessarily implies the presentation of two different words while only one word had to be processed in the first item condition. However, it was shown that both item STM conditions activated separate “item STM areas” compared to the order STM condition: Relative to both item STM conditions, the order condition showed consistently greater responses in the right, but not in the left, IPS. Both item conditions also showed increased activation in left posterior superior temporal areas associated with phonological / phonetic processing as well as in the bilateral fusiform gyrus associated with orthographic processing and also yielded increased activation peaks in the right insula, the posterior cingulate and the occipital cortex. As the functional imaging results showed virtually no differences between these two item recognition tasks but performance on the tasks differed in that item_2w task and order task were more comparable at behavioural levels (participants were a lot faster in the item_1w task compared to the item_2w task and the order task), only the item_2w task was used in the studies in Chapters 2, 3 and 5 in this thesis. Taken together, for the item recognition task, some neuroimaging evidence suggests stronger item involvement compared to order involvement but behavioural correlation analysis definitely implies strong involvement of serial order processes too.

In conclusion, the data in this chapter showed that order STM correlated with L1-type new word learning but not L2-type learning. Intercorrelations between different item and order STM tasks used in the different studies in this thesis revealed that the tasks are somewhat related but it is certainly not the case that they are identical in what they are indexing. Importantly, the cognitive processes involved in item recognition STM seem to overlap strongly with the ones measuring order STM.

Chapter 6: General Discussion and Conclusion

This thesis addressed two key issues. The first was the extent to which verbal short-term memory for item and order information can be differentiated in terms of their underlying neural mechanisms. The second was to analyze the relative contributions of item and order STM to vocabulary learning in BL and ML children and ML adults.

The first issue was addressed with four studies. Three used electroencephalography (EEG) with ML English adults, BL German/English adults and ML English children. The aim was to determine whether there is any evidence that the two types of verbal STM have different neural signatures. The fourth study used transcranial magnetic stimulation (TMS) in ML English adults to test the hypothesis that a specific region of parietal cortex, the right intraparietal sulcus (IPS), is involved in order STM but not item STM. The second issue was addressed by two behavioural studies. The first was a large-scale longitudinal study testing item and order STM in relation to natural vocabulary acquisition in 7 to 10 year old BL German/English children and ML German children. The children were tested once in the beginning and once in the end of the school year. In addition, ML English children starting to learn French as a second language (L2) were examined in the end of the school year. This latter group provided a second age-matched ML control group against which to compare the BL children. The second behavioural study explored the relationship of item and order STM with new-word-learning in ML English adults using artificially-created new words.

A brief overview of the key results from each of the studies is provided below.

The aim of the studies presented in Chapter 2 was to follow up the results of fMRI studies which suggest that item and order STM are supported by different neural mechanisms (Henson, et al., 2000; Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006; Marshuetz, et al., 2000), and to determine whether the two tasks can also be differentiated using EEG.

In support of other studies reviewed in Chapter 1, Sections 4, 6, 7, and 8, ML adults generated larger P300 and LPC amplitudes in order STM compared to item STM tasks. The P300 has been argued to be related to context updating in working memory (Donchin, 1981; Fabiani et al., 1986; Nittono et al., 1999; Howard & Polich, 1985; Blumhardt, 1996; Pelosi et al., 1992, 1998; Starr & Barrett, 1987; Key, Dove & Maguire, 2005; Polich, 2007). Therefore one possible interpretation of the present results is that order STM tasks involve more context updating than when remembering item identity alone. During order STM tasks the position of each item has to be remembered in addition to remembering the identity of each item. In order to establish serial order information one needs to know the context, i.e. what was before and what was after a given stimuli, whereas for item information, only the general context is needed (i.e., was a stimulus in a given stimuli list or not).

BL adults processed item and order tasks highly similarly. The only difference in neural activation in the BL group between item and order STM was that item STM showed more positive amplitudes compared to order STM in frontal regions during the LPC time window. Item STM tasks involve higher phonological and orthographic processing (Binder, et al., 2000; Bolger, Perfetti, & Schneider, 2005; Scott, Blank, Rosen, & Wise, 2000) compared to the order STM task which is designed to tap into areas assumed to reflect the updating and grouped rehearsal of serial order information (Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006). It was suggested that the higher amplitude in the item STM task in BL speakers might reflect the need of additional cognitive recourses, especially as the task was performed in their second language.

The next analysis compared ML and BL adults. Differences were expected in order STM processing but not item STM processing which was confirmed. It was argued that BLs and MLs remember the identities of the items in the list similarly but not the serial position of the items. This could indicate that BLs need less cognitive involvement to perform the order STM task than ML adults.

Study 3 investigated ML children´s processing of item and order STM. No significant differences in amplitude emerged in P200, but in the P300 and LPC components order STM elicited more positivity compared to item STM in frontal electrodes. It was argued, that (like in ML adults) order STM required more demanding retrieval processes compared to item STM in ML children. However, in the LPC window, item STM elicited more positivity compared to order STM in parietal regions. It was suggested that ML children rely heavily on the lexical phonological network when performing verbal STM tasks (similarly to ML adults see Chapter 2, Section 5 or also Adam & Collins, 1978; B. R. Dunn, et al., 1998).

In the final analysis of Chapter 2, ERP data of ML adults and ML children were compared. The hypothesis that item STM will be processed differently by the two groups due to poorer knowledge of phonological, orthographic and semantic properties of vocabulary items in ML children compared to ML adults was confirmed to some extent. The results indicated that item verbal STM undergoes important changes from childhood to adulthood in monolingual speakers as reflected by differences in the LPC component. ML adults showed less positive mean amplitudes when compared to ML children in the left hemisphere for item and order tasks and also less positive mean amplitudes for the item STM task in parietal right regions when compared to ML children. These developmental changes might be due to differences in representations in long-term lexical or semantic memories (see e.g., Cycowicz, et al., 2001), that are less well established for children than for adults, and make it more difficult for children to memorize a number of items. This difference is also reflected in behavioural data, as children show significantly lower accuracy rates than adults indicating the task overall was more difficult for them (and in fact LPC has been found to reflect subjective difficulty in performing a task, see Pelosi, et al., 1992). It was concluded that some similar age-independent components are used in monolingual speakers for item and order verbal STM tasks but that there are also developmental trends.

Taken together, the findings in the EEG studies reported in Chapter 2 support previous research that suggests that item and order STM have different underlying neural mechanisms (Henson, et al., 2000; Majerus, et al., 2007; Majerus, Belayachi, et al., 2008; Majerus, Poncelet, Van der Linden, et al., 2006; Marshuetz, et al., 2000) as well as various verbal STM models that differentiate between item and order components (i.e., Botvinick & Plaut, 2006; Brown, et al., 1999; Burgess & Hitch, 1999; Gupta, 1996; Majerus, 2008).

The TMS study in Chapter 3 aimed to investigate the role of the intra parietal sulcus (IPS) in order and item verbal STM in ML English speakers. It was hypothesized that impairing the left IPS should affect both order and item verbal STM in similar ways (i.e. slow down reaction times or lower accuracy rate) compared to impairing a control-site. Impairment of the right IPS on the other hand should only affect reaction times or accuracy of the order STM task but not the item STM task as indicated by recent fMRI studies (see e.g., Henson, et al., 2000; Majerus, et al., 2007; Majerus, Poncelet, Van der Linden, et al., 2006; Marshuetz, et al., 2000). Results confirmed the importance of the left IPS in both item and order verbal STM processes in monolingual English speakers: TMS over the left IPS resulted in an increase in errors on both item and order tasks compared to a control condition. However, there was no evidence for right IPS being involved in order or item processing. Hence the importance of right IPS for serial order processing could not be confirmed.

In Chapter 4, the role of item and order STM in vocabulary acquisition was investigated in a longitudinal study with BL and ML children. The aim was to determine the developmental pathways of item and order STM processes and to relate them to vocabulary development. It was shown that English order STM is a successful predictor of vocabulary acquisition in the less dominant language English in the end of the school year for bilingual children who are learning in an immersion context. Both, memory for item identity and order STM were predictors of monolingual vocabulary acquisition for German ML children in the end of the school year. For ML English children learning French as a second language, no correlations were found between item and order STM and vocabulary knowledge of the second language French. It was argued that this finding was very likely due to floor effects in the second language, i.e. the children were rather “pure monolinguals”. In the English ML children English order STM correlated significantly with English (L1) vocabulary scores.

BL children who master more than one language fluently outperformed monolingual children only mastering one language fluently in the order STM task. From this finding it was concluded that order STM seems to be important in language acquisition. However, the results could also reflect higher non-verbal reasoning skills of the BL children (see Leclercq & Majerus, 2010). On the other hand, ML English children outperformed BL children on the English item STM which further strengthens the claim that item STM is highly language dependent. ML children are more exposed to the one only language they speak which seems to enhance their item STM skills (see also Messer, et al., 2010; Storkel, 2001, 2003).

It has been suggested that in ML children order STM is an important early predictor, followed by item STM becoming a stronger predictor at later age (see Majerus et al., 2006). The findings in this thesis expand this hypothesis: Order STM seems to be an important early predictor when vocabulary knowledge is not yet well established in both ML and (at least highly proficient) BL children. Order STM was found to be the strongest predictor of vocabulary acquisition in the less dominant language in BL children. Yet it cannot be overlooked that the language environment the children grow up in also affects the influence of item and order STM on their vocabulary knowledge. This was suggested as different results were found for German, English and French as a second language.

Taken together, the findings in Chapter 4 looking at behavioural child data also provide support to recent verbal STM models that differentiate between item and order components (i.e., Botvinick & Plaut, 2006; Brown, et al., 1999; Burgess & Hitch, 1999; Gupta, 1996; Majerus, 2008). In addition, they give crucial new insights the relation of item and order STM to vocabulary acquisition: The relationship of item and order STM and vocabulary knowledge seems highly sensitive to the level of vocabulary knowledge (as found by order STM being a more important predictor for the less dominant language in BL children) as well as language environment (as different effects were found for BL children and English and German ML children) and age (as found by order STM being a more important predictor in younger BL children compared to older BL children).

The last study in Chapter 5 investigated the relationship of item and order STM on new-word learning in ML English adults. It was expected that order STM would be more highly related to nonword learning than item STM.

However, the results did not support the hypothesis that memory for item identity or serial order in verbal STM make important contributions to the acquisition of new vocabulary as previously found in monolingual children and adults (see i.e., Majerus, Poncelet, Elsen, et al., 2006; see also Chapter 4). The nonwords used in the vocabulary learning task might have been too similar to the native language English which then might have made item and order STM non-relevant as predictors (see Chapter 4 for a discussion of level of vocabulary knowledge and the predictive value of item and order STM). Instead, non-verbal IQ was found to be the most predominant predictor of native like language learning in ML English speaking adults. However, it must be acknowledged that the study was quite small scale and may have failed to detect significant effects.

Importantly, in a second part of the study, a correlational analysis between the different item and order STM tasks used in this thesis revealed that the tasks used are measuring somewhat related processes but it is certainly not the case that they are identical in what they are indexing. The cognitive processes involved in item recognition STM overlap somewhat with the ones with order reconstruction STM task. It is hence concluded that item and order STM tasks are not completely independent of each other.

1. The Distinction of Item and Order STM

Previous research has suggested that (at least partially) distinct cognitive processes underlie the processing and storage of item and order information (see Chapter 1, Section 4 onwards for an extensive review; Brown, et al., 2000; Burgess & Hitch, 1992, 1999; Gupta, 2003; Gupta & MacWhinney, 1997). This distinction can also be supported on analytic/definitional ground (i.e., it is possible to imagine item memory without order memory and order memory can be tested by giving items and telling people that these items had previously been in the list, so that the item memory component is very much reduced). The item STM task is thought to need the lexical phonological network more that the order task (because the item STM tasks require checking whether particular items were in the list, whereas, in the order task, it is given that the two presented items were in the list). Order STM on the other hand is thought to tap into distinct serial order processing mechanisms.

Estes (1972) points out that according to his perturbation model it is important to remember both the item and its within list position for correct order recall. The distinction between conjunctive versus independent representations of item and position in context based models has often been linked to the claim that serial recall involves a two stage process: a first stage where position information is retrieved and a second stage at which item identification occurs (see e.g., Henson, 1998). In the model by Burgess and Hitch (1999) the sounds of new words and their pronunciation are learned by strengthening connections between phonological and item representations whereas memory for serial order can be improved by strengthening connections between items and context/timing representations. According to Gupta´s model (2003), the production of a word form is a serially ordered process and therefore, the representation of a word form at the Phonological Chunk Layer has to be able to produce a specific sequence of phonemes at the Phoneme Layer. Majerus´ model (2008) includes a language system which contains a sub-lexical network of phonological, lexical and semantic representations, which are used to process verbal "item information". An additional system is used for the processing of serial order information. All these models hence assume independence of item and order components where the order component often involves a separate system including "time" or "position" while the item component comprises (sub-)lexical phonological representations, semantic representations and is influenced by presentation modality and item familiarity.

Findings in this thesis have revealed some evidence to support the view that the distinction of item and order STM is a useful one: Tasks that maximised verbal STM for item information and serial order information showed distinct neural patterns in EEG in ML English speaking adults and ML English speaking children as well as some differences in BL German/English speaking adults. In a behavioural study, order STM but not item STM was the most dominant predictor in vocabulary knowledge in the end of the school year in 7 to 10 year old highly proficient BL German/English children. In addition, highly proficient BL children outperformed ML children in an order STM task, but English ML children outperformed BL children on an English item STM tasks.

Yet on the basis of the studies in this thesis, the distinction of item and order STM may need to be modified somewhat. It seems that the distinction may be clearer in some groups of participants, or at certain stages of language learning. Also it is clear, that large amounts of overlapping cognitive processes are involved in tasks that assess item and order STM.

Importantly, only English order STM predicted vocabulary knowledge in English at the end of the school year in highly proficient BL children. But neither item nor order STM was found a significant predictor variable for German vocabulary knowledge at the end of the school year. It was discussed that this might be due to the fact that English is the less dominant language in the BL children, as they grow up in Austria, a German speaking environment. As discussed in Chapter 4, Section 5, phonological STM (as measured with nonword repetition in a study by Gathercole, et al., 1992), or more specifically order STM (as found by Majerus, Poncelet, Greffe, et al., 2006), might only be a better predictor of vocabulary growth in children when high pressure is put on vocabulary gain. Once existent vocabulary expands, the learners might be more able to make use of analogies with existing vocabulary items to learn the phonological forms of new words, thus reducing the short-term phonological memory load involved in acquiring new words (see Gathercole, et al., 1991). Indeed, a subgroup analysis of the BL children revealed that order STM was an important predictor in the less dominant language, i.e. English order STM predicted English vocabulary in German dominant children and German order STM predicted German vocabulary in English dominant children, while for the rest of the children only existent vocabulary in a given language predicted vocabulary growth. In addition, English order STM was significantly correlated to English vocabulary in the end of the school year only in children in Year 2 and 3 but not Year 4. This finding further indicates that younger children compared to older children might have used verbal order STM more to learn English while older children might have used different strategies. The finding could reflect that as the learner becomes more familiar with the phonology of a second language, it may be that semantic and conceptual learning take over the language learning process (see e.g., Morra & Camba, 2009).

Only item STM was significantly correlated to German passive vocabulary knowledge at the end of the school year in German ML children. After taking into account German vocabulary knowledge at Time 1 the correlation no longer remained significant. It was argued that for the German language, phonological sensitivity (i.e. item STM) could be more important as this factor predicted learning of long nonwords in the Morra and Camba (2009) study. Note that German has relatively longer words compared to English. In addition it was argued that the German language itself might enhance item STM, especially once children go to school and start to learn how to read and write, as it is a more phonetically accurate language in terms of grapheme-phoneme-correspondence regularity compared to English.

In English ML children learning French English order STM was only correlated to the native language (English) but not the second language (French). It must be noted however, that the groups of German ML children and English ML children learning French was relatively small, only comprising of about 35 children and hence future research should investigate the question with a larger group of children to increase the test power (for further discussion of future research see Section 2 in this chapter). In a group of ML English speaking adults, multiple regression analysis could not confirm previous findings of order STM having the strongest predictive value for new word learning, as previously found in ML adults (Majerus, Poncelet, Elsen, et al., 2006) and ML children (Majerus, Poncelet, Greffe, et al., 2006) but instead non-verbal IQ was the significant predictor for L1-type non-word learning.

Taken together, the findings in this thesis indicate that item and order STM can successfully be identified as separate components of verbal STM (as found in EEG studies and behavioural data in this thesis). However this distinction might only be a useful one in the prediction of vocabulary knowledge in a specific time window of level of vocabulary knowledge, and even varying from language to language. Order STM might only be a relevant predictor of vocabulary acquisition once a language has been learned to certain proficiency (as shown by non-significant results in ML English children learning French but significant results of the less dominant language English in highly proficient BL children; see also Majerus, Poncelet, Greffe et al., 2006). Other factors might take over as predictors once certain knowledge of language level is achieved such as vocabulary knowledge (as shown in the more dominant language German in highly proficient BL children) or non-verbal IQ (as shown in English ML adults).

2. Limitations and Future Research

In the first study with ML adults (see Chapter 2, Section 5) one major criticism relates to the behavioural differences between the tasks: ML adults were slower but more accurate in order STM than item STM. Even though the analysis was limited to correct trials, the differences in ERPs might still reflect the fact that one task was more difficult than the other[44]. Future ERP studies should use tasks that are equally difficult. This is especially important for ERP studies as the waveforms can also reflect behavioural difficulties and hence might not purely reflect differences in the neural systems supporting performance on item and order STM tasks[45].

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[44] Note that in the TMS study presented in Chapter 3 ML English speaking adults were also slower in the order STM task compared to item STM task. In the sample of ML English speaking adults presented in Chapter 5, no behavioural differences between item and order STM tasks were found. Compared to the EEG study, the study presented in Chapter 5 was purely behavioural which might have influenced performance on the tasks.

[45] Note that item and order STM tasks also revealed different behavioural patterns in recent fMRI findings investigating item and order STM differences (Majerus, et al., 2007; Majerus, D'Argembeau, et al., 2009; Majerus, Poncelet, Van der Linden, et al., 2006).

Another concern arises when comparing ERP data across groups, i.e. comparing ML speakers with BL speakers or adults with children. Even though the tasks were designed to be matched as closely as possible in terms of linguistic features (i.e. word frequency, number of syllables, number of phonemes etc), the ERPs of the different groups might have picked up group specific differences. For example, the word frequencies of the words used in the tasks were based on ML English speaking adults. These words were most likely less frequent in BL adults (who might process words in their second language differently compared to their first) and ML children (who have less language experience than ML adults simply due to their age). One possible way of avoiding word frequency effects would be using non-linguistic material (such as pictures) rather than words. This can make between-group comparisons easier to interpret. In addition, using picture-stimuli and comparing them to word stimuli can be use to investigate if similar results for amplitude differences in item and order STM can be found across modality (see e.g., Majerus, et al., 2007).

In the ERP study only three time windows (P200, P300 and LPC) were analyzed, on the assumption that they were most related to verbal STM tasks. They were selected by reviewing the previous memory literature. Another way of analyzing the data could have been to take a more exploratory approach. This is typically done by looking at the waveforms and visually exploring possible differences which then are statistically analyzed. This form of analysis could potentially find more precise differences between tasks, but it is also associated with difficulties in interpreting the results. Limited literature references might be available against which to compare any findings.

One concern of the TMS study in Chapter 3 is the question of precise localisation. For future research it would be preferable to use structural MRI scans throughout all participants. In addition, more precise location methods such as mathematical models are recommended to co-register a series of neural land-marks using MRIcro and MiniBIRD coordinates. Having an fMRI scan for each participant during which they perform item and order STM tasks could help to identify the precise location of those areas of the cortex that are most involved in the tasks. This way the co-ordinates for each participant can be stimulated accurately.

To investigate possible language-related differences in item and order STM further, a future study could be conducted to see if differences in left and right IPS disruption using TMS can be found in high proficient bilingual speakers compared to low proficient BL speakers or ML speakers.

In addition to precise measures of location, alternative regions could be investigated. As mentioned in Chapter 3, Section 6, a possible region that might be worth investigating more regarding order STM is the left dorsolateral prefrontal cortex (DLPFC, see e.g., Henson, et al., 2000). However as discussed in Section 6 of Chapter 3 the investigation of frontal areas can be problematic with TMS method.

A limitation of the study reported in Chapter 4 with BL and ML primary school children is the relatively small group size of the BL subgroups (i.e. when the group was divided by language dominancy and school year) and ML groups. This made it impossible to investigate language dominancy in the separate grades (i.e. Year 2, 3, and 4) which could have given further insight into the individual importance of English or German language knowledge. The small size of the ML control groups made it not possible to investigate age effects further (~10 children per school year in each ML control group).

It would have been interesting to investigate English (L2) item and order skills of the monolingual German sample to directly compare them to the English ML sample learning French as L2. Due to time limitation in data acquisition this was not possible.

Also due to time limitations, the English ML group was tested at only one time point. Hence existent vocabulary knowledge from the beginning of the school year could not be taken into account in the analysis. This would have complemented current findings in ML German and BL children.

In the English ML group it was not possible to use the French order memory task in the L2 learning English group as the animal words were too difficult for the children. Using e.g. colour names could have been a solution and might be considered for future research with beginning language learners.

Future research should investigate whether similar results can also be found with other languages or in other age groups. For example it would have been interesting to see if similar results could have been found in German-English BL children aged 4 to 6 years old. A ML German speaking control group at this age could have provided direct comparison to a study by Majerus, Poncelet, Greffe et al. (2006) and Leclercq and Majerus (2010). Future research should be conducted with similar tasks in other languages to investigate if similar results for ML and BL children could be found.

The studies were unable to address the causality issue of the relationship between item STM, order STM and vocabulary knowledge. Testing item and order STM twice as was done with vocabulary knowledge would allow investigating causality by using a cross-lag analysis as previously done by Gathercole, Willis, Emslie and Baddeley (1992). Unfortunately due to time limitation in data acquisition this was not possible. In the future it will be interesting to look at monolingual children, bilingual children and children who are learning a second language using a cross lag design.

With only 32 participants the behavioural study with ML adults in Chapter 5 has a quite small sample size, and an even smaller sample size (N=21) for calculating some of the intercorrelations between the different item and order STM tasks. This study can, therefore, really only be used as pilot study and the questions it addresses should be further investigated with a larger group of participants. A future study with a larger participant pool can then also use multiple regression analysis in order to evaluate the predictive value of item or order STM on new word learning.

In order to further investigate whether the differences between item and order STM in ML English speakers are a general finding or, rather, language specific, the study of ML speakers should be repeated with a group of ML speakers with a different native language, e.g. German. Compared to English, German is a more flexible language in terms of sentence structure and word order and hence that fact alone could change participants processing of item and order verbal STM.

In addition, it could be interesting to administer similar new-word learning tasks to bilingual participants to find out if order STM compared to item STM might be a stronger predictor of vocabulary learning in this group as found in previous studies.

Another important task for future studies is to administer a new-word-learning paradigm that is more sensible in comparing native-like language acquisition and new-language acquisition. This could be achieved by including more complex foreign-based words in the task. However, if new phonological sounds are introduced this could also distort new-word learning results, as it might take participants more time or require a greater contribution from other cognitive factors like attention or higher phonological skills, to successfully complete this task. This in turn could make it difficult to compare this harder learning task to an easier learning task that did not involve new sounds. It seems a quite complex process inventing a completely satisfactory task that compares L1 with L2 based new word learning, and it might be easier to look at longitudinal vocabulary data in developmental samples, i.e. monolingual children learning a second language.

3. Conclusion

Taken together, the following general conclusions can be drawn from the data collected for this thesis: Some evidence has been found to support the view that the distinction of item and order STM is a useful one. The results of the EEG data suggest differences in patterns of neuro-electrical activity for ML adults, BL adults and ML children when they are performing item STM and order STM tasks. Yet it cannot be ruled out that some of the differences in brain activity might be explained by levels of task performance. The TMS data did not reveal evidence for any differences in item and order STM processing in left and right IPS. This might have been due to inexact localization methods, investigating an inappropriate brain area or using an unsuitable TMS protocol. Some evidence from the children´s study suggests that order STM is more important in vocabulary acquisition in the less dominant language in BL children. Order STM was also more highly correlated to vocabulary at the end of the school year in 7-10 year old English ML children and to L1 (English)-phonetic based new words in a paired associate picture-nonword learning task in English ML university students.

Findings in this thesis suggest that order STM is important for new word learning in one´s native language, where (at least some) exposure to this language is present, but not in complete novice language learners. The latter finding, that order STM is not as important in complete novice language learners, was reflected in no correlations between item and order STM in 7-10 year old ML English children learning French and no correlation of item and order STM in L2 (Czech)-phonetic based new words in a paired associate picture-nonword learning task in English ML university students. In order to fully understand the importance of item and order STM on vocabulary learning, longitudinal studies across several years starting from early language acquisition with ML children, BL children (who acquire two languages from birth) and ML children acquiring a second language later in life would be helpful.

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Z

List of Appendices

Appendix A1: EEG – Consent form Adults

Participant No.:

Information for monolingual participants

Name: ________________
E-Mail: ________________
Signature: ______________

The Purpose of the Experiment

The investigation of electrophysiological aspects of short term memory processing.

What you will be required to do

You will be asked to brush your hair before a Netstation sensor net is applied to your head. You will then be seated in a separate room and presented with four different trials, an order memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred in this order), an item memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred), an order control task (see four words, decide whether they were presented in an alphabetical order, do mathematical decision task) and an item control task (see four words, decide whether they have two letters equal to each other, do mathematical decision task). These tasks will be given to you three times in a different order and it will take about an hour to complete the task. Electrophysiological responses will be recorded throughout.

Precautions

You should *not* take part if you:

1. do not speak English as your first language.
2. speak more then one language fluently
3. suffer from any neurological impairments (e.g. epilepsy, metal implants)
4. suffer from any skin allergies
5. take medication for depression
6. have dyslexia or any other learning disabilities
7. have a cold or flu or getting over a cold or flu at the time you intend to participate
8. have suffered severe head injury in your lifetime (i.e. loss of unconsciousness for more than 30 minutes)

On completion of the study you will receive two hours worth of course credits.

If you have any queries, please contact:

Kathrin Klingebiel,
3B4, Pevensey 2 Building, Psychology, University of Sussex, BN1 9QG.
E-mail: K.A.M.Klingebiel@sussex.ac.uk
Tel.: 01273 87 6649

Taking part is entirely voluntary and confidential. **Remember, you may withdraw from this study at any time.**

Participant No.:

Information for bilingual participants

Name: ______________
E-Mail: ______________
Signature: ____________

The Purpose of the Experiment

The investigation of electrophysiological aspects of short term memory processing.

What you will be required to do

You will be asked to brush your hair before a Netstation sensor net is applied to your head. You will then be seated in a separate room and presented with four different trials, an order memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred in this order), an item memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred), an order control task (see four words, decide whether they were presented in an alphabetical order, do mathematical decision task) and an item control task (see four words, decide whether they have two letters equal to each other, do mathematical decision task). These tasks will be given to you three times in a different order and it will take about an hour to complete the task. Electrophysiological responses will be recorded throughout. A second part, which will take place in February, will contain a short language screening of your English and German knowledge.

Precautions

You should *not* take part if you:

1. do not speak German as your first language.
2. do not speak English fluent
3. suffer from any neurological impairments (e.g. epilepsy, metal implants)
4. suffer from any skin allergies
5. take medication for depression
6. have dyslexia or any other learning disabilities
7. have a cold or flu or getting over a cold or flu at the time you intend to participate
8. have suffered severe head injury in your lifetime (i.e. loss of unconsciousness for more than 30 minutes)

On completion of the study you will receive two hours worth of course credits or 10 GBP. This will only be paid if you attend both parts of the study (EEG & Language screening in February).

If you have any queries, please contact:

Kathrin Klingebiel,
3B4, Pevensey 2 Building, Psychology, University of Sussex, BN1 9QG.
E-mail: K.A.M.Klingebiel@sussex.ac.uk
Tel.: 01273 87 6649

Taking part is entirely voluntary and confidential. **Remember, you may withdraw from this study at any time.**

Volunteer Consent Form

I have read and had explained to me the attached information sheet, which I have signed and of which I retain a copy. The nature and purpose of the psychological testing has been explained to me. I am aware that I have the right to withdraw from the experiment at any time.

I fully understand the nature and purpose of the study and give my consent to participate.

Name: ______________________________

Signed: ______________________________

Date: ___ / ___ / __

Appendix A2: EEG – Questionnaire for bilingual participants

Datum: _______________ Name:___________________________________

Questionnaire English

How old where you, when you started to learn English?

How many years did you have English lectures?

Do you have English lectures at the moment?

Since how many years do you actively use English (not during school)?

How many years have you lived in an English speaking country?

Which other languages have you learned?

1. ____
2. ____
3. ____

How many years/months?

1. ____
2. ____
3. ____

How well do you speak them?

Some words fluent

1.

O-----------O-----------O-----------O-----------O-----------O-----------O

2.

O-----------O-----------O-----------O-----------O-----------O-----------O

3.

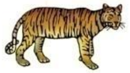
O-----------O-----------O-----------O-----------O-----------O-----------O

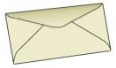
Appendix A3: EEG – Picture naming stimuli for bilingual participants

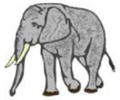
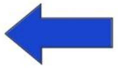
Picture	correct English respond	correct German respond
	snail	Schnecke
	bulb, light bulb	Glühbirne
	pineapple	Ananas
	open-end spanner, wrench	Schraubenschlüssel, Schraubschlüssel
	mouse	Maus
	violin	Geige, Violine
	lion	Löwe

	orange	Orange
	toaster	Toaster
	pig	Schwein
	lorry, truck	Lastwagen, Laster, Kraftfahrzeug, LKW
	screw	Schraube
	balloon	Luftballon, Ballon
	coat, jacket	Mantel, Jacke
	anchor	Anker
	guitar	Gitarre

	duck	Ente
	cigarette	Zigarette
	cake	Kuchen, Torte
	drum	Trommel
	belt	Gürtel
	butterfly	Schmetterling, Falter
	bow tie	Schleife
	flute, clarinet	Querflöte, Flöte, Klarinette
	leaf	Blatt
	shoe	Schuh

	lamp, light	Lampe
	screwdriver	Schraubenzieher
	snowman	Schneemann
	tiger	Tiger
	pear	Birne
	pliers, tongs	Zange
	trumpet	Trompete
	pushchair, stroller, pram, buggy	Kinderwagen
	ruler	Lineal

	vase, bowl	Vase
	banana	Banane
	doll	Puppe
	flag	Fahne, Flagge, Fähnchen
	envelope	Briefumschlag, Umschlag, Kuvert
	kangaroo	Känguru
	ashtray	Aschenbecher
	comb	Kamm
	frog	Frosch

	cigar	Zigarre
	carrot	Möhre, Mohrrübe, Karotte
	elephant	Elephant
	arrow	Pfeil

Appendix A4: EEG / TMS – Instructions for adults

In this experiment, you will see four words displayed sequentially, followed by a response trial.

In the ORDER short-term memory conditions, you have to judge whether the two words presented during the recognition display had occurred in that order or not.

In the ITEM short-term memory condition, you have to judge whether the two words presented during the recognition display had occurred in the list or not.

We will now start with 25 trials for the ORDER short-term memory condition.

Remember:
You have to focus on the ORDER of presentation of the items and to recognize their order.

REPORT

RETELL

ATTEST

LOCUS

RETELL ATTEST

We will now continue with 25 trials for the ITEM short-term memory condition.

Remember:
You have to check whether there is a word with two contiguous identical letters and then check the associated arithmetical operation

LEGION

LOTUS

MARGIN

MANTLE

LESION LOTUS

Appendix A5: EEG – Consent form Children

Dear parents/guardians

All information on this sheet will be treated with confidentiality and the identity of you and your child will remain anonymous. You and your child can withdraw participation from the study at any time.

The Purpose of the Experiment
Investigating electrophysiological aspects of short term memory processing in 8-11 year olds

What your child will be required to do
He/she will be asked to wash and brush his/her hair with baby shampoo before a Netstation sensor net is applied to his/her head. Your child will then be seated in a separate room and presented with four different trials: a word order game (see four words, memorize them and decide whether or not two simultaneously presented words occurred in this order), a memory game (see four words, memorize them and decide whether or not two simultaneously presented words occurred), an alphabet game (see four words, decide whether they were presented in an alphabetical order, do mathematical decision task) and a double-letter game (see four words, decide whether they have two letters equal to each other, do mathematical decision task). These tasks will be given to your child two to three times in a different order and it will take about an hour to complete the task (without break and without preparation). Electrophysiological responses will be recorded throughout.

Precautions
Your child should *not* take part if he/she:

1. Does not speak English as your first language.
2. Speaks more than one language fluently
3. Suffers from any neurological impairments (e.g. epilepsy, metal implants)
4. Suffers from any skin allergies
5. Takes medication for depression or AD(H)D
6. Has dyslexia, any other learning disabilities or AD(H)D
7. Has a cold or flu or getting over a cold or flu at the time he/she intends to participate
8. Has suffered severe head injury in his/her lifetime (i.e. loss of unconsciousness for more than 30 minutes)

On completion of the study you will receive 25,- pounds.

If you have any queries, please contact:

Kathrin Klingebiel,
3B4, Pevensey 2 Building, Psychology, University of Sussex, BN1 9QG.
E-mail: K.A.M.Klingebiel@sussex.ac.uk
Tel.: 01273 87 6649

Taking part is entirely voluntary and confidential.
Remember, you and your child may withdraw from this study at any time.

Volunteer Consent Form

I have read and had explained to me the attached information sheet, which I have signed and of which I retain a copy. The nature and purpose of the psychological testing has been explained to me. I am aware that I have the right to withdraw from the experiment at any time.

Child's Name: ____

Date of birth: ______________________ Boy ◻ Girl ◻

Parent/Guardian:

Name: ………………………………………………………………………………………

Telephone: ………………………………………………………………………………

Email: ………………………………………………………………………………………

I fully understand the nature and purpose of the study and give my consent for my child to participate.

Name: ____________________________________

Signed: ____________________________________

Date: __ / __ / 2009

Appendix A6: EEG – Instructions for children

BRAIN GAME
for children between 9 and 11

WELCOME

The brain game is made up of 2 mini games:
Word Order Game and Memory Game.

In each game you will see 4 words one at a time. But in each game you will have to do something different with the words:

Word Order Game

In the word order game you will see the 4 words come up one at a time. Then, you will see 2 words on the screen. These will be two of the words that you saw before. You will have to decide, if the words are in the same order that you saw them before or not. Press the red grumpy if they where not in the same order and the green smiley if they where.

Memory Game

In the memory game you will see the 4 words come up one at a time. Then, you will see 2 words on the screen. These will be either two of the words that you saw before or one of the words will be a little bit different. Be careful! You have to pay close attention! If they where exactly the same as before press the green smiley and if not, press the red grumpy.

We will now continue with 25 trials for the Word Order Game.

Remember:
You have to decide if the words are in the same order that you saw them before or not.

REPORT

RETELL

ATTEST

LOCUS

RETELL ATTEST

We will now continue with 25 trials for the Memory Game.

Remember:
You have to decide if the words where exactly the same as before.

LEGION

LOTUS

MARGIN

MANTLE

LESION LOTUS

Well done!

Thank you very much!

Appendix A7: Strengths and weaknesses of EEG techniques

Weaknesses

Compared to behavioural studies, ERP data show a large amount of variability across single trials when compared to behavioural data. Hence, a large number of trials are required to gain accurate measurements. Picton et al. (2000) point out that at least 50 good trials per subject in each condition are needed – on the other hand only 20 can give insights in most behavioural studies.

Compared to other neuropsychological methods, EEG only offers low spatial resolution. The spatial resolution of ERP measurements is limited both by theory and by our present technology. For example, it is more sensitive to potentials closer to the surface then to deeper layers of the cortex. Yet, multichannel recordings can allow us to estimate the intra-cerebral locations of certain cerebral processes (Picton et al., 2000). Modern EEGs can use as much as 256 channels to record brain activity (see e.g. www.egi.com).

A common problem in ERP measures is the so called inverse problem: It is currently impossible to reconstruct the exact source of the electrical activity in the brain. Some currents might produce potentials that might cancel each other out, others might reflect in brain surfaces that do not cover the source-area in the brain (LIT). It is difficult to identify brain regions that are responsible for generating or modulating cognitive ERPs.

So called inverse solutions are source-localization programs, such as Loretta (Pascual-Marqui, Michel, & Lehmann, 1994), which are based on head models. However, as Slotnick (2005) points out: “Source localization has many complex aspects, including head modelling, iterative model fitting, and user specific constraints. For this reason, it is unlikely that there will ever be one correct method to conduct source localization. Rather, the field of source localization is expected to continue on its course of rapid evolution” (p.161). Thus, it is difficult to draw strong conclusions on the basis of ERP data alone about the brain regions involved in task-related cognitive operations.

Another weakness of ERPs is that they can only be used to study event-dependent time-locked processes. Hence, activities such as rehearsal or free recall are not very suitable to be studied with ERP techniques as there is no obvious event.

Meninges, cerebrospinal fluid and skull disturb the EEG signal. To minimize this problem it is important that participants wash their hair before being tested and alcohol pads are used to clean the skin where electrodes are applied. This can make it an uncomfortable experience for participants as they might suffer skin reactions from shampoo, electric wipes, gel or electrolytes that are used in the process.

Another disadvantage of EEG is that it is highly sensitive to movement – even eye blinks can cause artefacts. This makes especially EEG studies with children and very active adults a challenge.

Strengths

The greatest advantage of EEG techniques is its great temporal resolution. It can detect changes within milliseconds. This is excellent as action potentials take about 0.5 to 130 milliseconds depending on the type of neuron (Anderson, 2005). ERPs can therefore accurately measure when processing activities take place in the human brain (Picton et al., 2000). This low temporal resolution allows upper-bound estimates of the time required by the nervous system to discriminate between different classes of stimuli (Rugg & Allan, 2000). Other neuroimaging methods such as fMRI or PET only have time resolutions between seconds and minutes.

ERPs can provide a window into the online processing between a stimulus and its behavioural response. This makes it possible to determine which temporal stages of processing are affected by a specific experimental manipulation. In memory studies one might be able to detect differences in encoding and retrieval phases.

Depending on the subject's behaviour during a task, ERPs can be formed after the experimental trials have been sorted into different conditions. Hence, it is easy to obtain and compare records of brain activity associated with different classes of response to the same experimental items, e.g. correctly remembered, false alarms, hits, misses etc. (Rugg & Allan, 2000).

ERPs can be used to investigate whether different experimental conditions engage functionally dissociable cognitive processes (Rugg & Allan, 2000). This rests on the assumption that there are strong grounds for proposing that the conditions engaged at least partially non-overlapping neural, and hence functional processes if two experimental conditions are associated with qualitatively different patterns of scalp electrical activity.

Compared to other imaging methods, EEG provides a rather low cost method for brain research.

Appendix A8: EEG / TMS – Stimuli list

	MeanLogFreq	NbGraph	NbPhon	NbSyll		MeanLogFreq	NbGraph	NbPhon	NbSyll
LEGION	2,07555	6	5	2	LESION	1,00000	6	5	2
LOTUS	1,53148	6	5	2	LOCUS	1,27875	5	5	2
TUTOR	2,66370	5	5	2	TUMOR	1,61278	5	5	2
CHARMER	1,44716	7	5	2	CHARTER	2,17319	7	5	2
TONIC	1,88649	5	5	2	TOPIC	2,69373	5	5	2
REPORT	3,41863	6	5	2	RESORT	2,54777	6	5	2
EJECT	1,77815	5	5	2	ELECT	2,79099	5	5	2
NOTICE	3,36605	6	5	2	NOVICE	1,89763	6	5	2
STABLE	2,48572	5	5	2	STAPLE	1,96848	5	5	2
CANKER	0,84510	6	5	2	CANTER	1,34242	6	5	2
CURLING	1,76343	7	5	2	CURVING	1,79934	7	5	2
RATING	2,01284	6	5	2	RACING	2,31597	6	5	2
MANTLE	1,86332	6	5	2	MANGLE	1,53148	6	5	2
MANURE	2,10037	6	5	2	MATURE	2,40483	6	5	2
CLOSER	2,70842	6	5	2	CLOVER	2,04532	6	5	2
CARBON	2,40824	6	5	2	CARTON	1,68124	6	5	2
NASAL	2,47276	5	5	2	NAVAL	3,36605	5	5	2
BANKER	2,40483	6	5	2	BANTER	1,07918	6	5	2
MARGIN	2,41664	6	5	2	MARTIN	2,81823	6	5	2
OUTLET	2,14613	6	5	2	OUTSET	2,00000	6	5	2
BALLOON	1,76343	7	5	2	BASSOON	0,47712	7	5	2
HUNGER	2,63749	6	5	2	HUNTER	2,65128	6	5	2
PLANNER	1,64345	7	5	2	PLATTER	1,54407	7	5	2
INVERT	1,92942	6	5	2	INSERT	2,31175	6	5	2
BOUNCER	1,23045	7	5	2	BOUNDER	0,69897	7	5	2
DECREE	1,85126	6	5	2	DEGREE	3,40637	6	5	2
LINING	1,87506	6	5	2	LIKING	2,04532	6	5	2
BARON	2,18469	5	5	2	BATON	1,95904	5	5	2
ARREST	2,77887	6	5	2	ATTEST	1,50515	6	5	2
RESELL	1,30103	6	5	2	RETELL	1,11394	6	5	2

Note: Mean LogFreq = Mean Logarithmic Frequency; NbGraph = Number of Graphemes; NbPhon = Number of Phonemes; NbSyll = Number of Syllables

Appendix B1: TMS consent form and questionnaire

Participant Information Sheet and Consent Form

You are being invited to take part in a research study.
Before you decide whether to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends, relatives and your GP if you wish. Ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to participate.

It is up to you to decide whether or not to take part. If you do decide to do so you will be given this information sheet to keep and be asked to sign consent from. If you decide to participate you are still free to withdraw at any time and without giving a reason.

The research aims to establish the role different parts of the brain play in serial order and item short-term-memory. We will use a technique called low-frequency repetitive transcranial magnetic stimulation (rTMS). This involves having a stimulating coil placed to your head. The coil releases a series of magnetic pulses (one pulse per second) for a period of 10 minutes per trial. This technique has been found to reduce the excitability of the neurons underlying the stimulating area for a short period of time after the stimulation has stopped. The effects are subtle, and are only revealed as very small changes in sensitive performance measures such as reaction times.
This technique is very useful for researchers interested in determining the role different brain areas play in controlling language.

The experiment will involve stimulation to two brain regions: the left and the right anterior intraparietal sulcus. The hemispheres will be stimulated in separate sessions. During the session you will complete an order memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred in this order) and an item memory task (see four words, memorize them and decide whether or not two simultaneously presented words occurred), these will occur whilst the effects of the coil are there. In order to determine the appropriate strength of stimulation, the first part of the experiment will begin with several single pulses over the part of your brain that controls hand movements. The pulses will increase in intensity until your left hand twitches. This is the intensity we will use. But as we will no longer be stimulating the part of your brain that controls hands movement your hand will not move. There will be two sessions each of them lasting about 2 hours.

Some participants may find that the rTMS causes a mild headache. This may be due to the contraction of the scalp and neck muscles caused by the magnetic pulses. If at any point you experience any discomfort during the procedure, inform the experimenter, and the stimulation will be immediately terminated. The stimulating coil also makes a loud click each time it releases a magnetic pulse. In order to minimize any discomfort this causes, you will be given some foam ear plugs. The coil can heat up if it is used for extended periods of time. This is very unlikely to occur within the five minutes given the low frequency of the pulses, and the coil temperature will be monitored constantly. If at any point the coil becomes uncomfortably warm, inform the experiment and the stimulation will be immediately terminated.

In a recent study, children who were administered TMS pulses rated the experience as les pleasant than watching TV, but more pleasant than a long car journey.

Repetitive transcranial magnetic stimulation has no known long term adverse effects. No known seizures have ever been recorded in studies using low frequency rTMS. In fact it is often used as a therapeutic treatment for patients with psychiatric disorders such as depression, and neurological disorders such as Parkinson's disease and epilepsy. However, as a precaution it is very important that you do not participate in this experiment if you have any personal or family history of epilepsy. As the magnetic field produced by the coil is quite strong, it is also important that you do not have any surgical implants that might be affected by the magnetic field, such as pacemakers or aneurysm clips. You will be asked to complete a screening questionnaire to ensure that of the exclusion criteria associated with the use of rTMS apply. And it is worth noting that one of those is that you have not consumed more than three units of alcohol in the last 24 hours.

You will receive 25 pounds for participating in this research.

If you have any questions concerning this study, please ask me at any time: Call 01273 876649 (office) or 0752 71 54 189 (mobile) or send an email to k.a.m.klingebiel@sussex.ac.uk.

Thank you,
Kathrin

Consent Form I - Participation

I have read and had explained to me the attached information sheet, which I have signed and of which I retain a copy. The nature and purpose of the psychological testing and the associated risks have been explained to me. I am aware that I have the right to withdraw from the experiment at any time.

I fully understand the nature and purpose of the study and give my full consent to participate.

Name:______________________________

Signed:________________________

Date: ____ / ____ / ____

Consent Form II – Structural Scan

In order to localise a specific brain region (in our case the left and right intraparietal sulcus) a structural brain scan will be used. We will use a 3D position measurement device called Ascension MiniBird to measure positions in your brain. In order to do this, you will have to give consent that we can use your brain scan that has been collected in a former fMRI study.

I agree that Dr. Brendan Weekes and Kathrin Klingebiel may use my structural brain scan, to localise the left and right intraparietal sulcus in their study. I have read and had explained to me what my structural brain scan is used for. The nature and purpose of the psychological testing and the associated risks have been explained to me. I am aware that I have the right to withdraw from the experiment at any time.

I fully understand the nature and purpose of the study and give my full consent to participate.

Name:______________________________

Signed:________________________

Date: ____ / ____ / ____

TMS Screening Questionnaire – adapted from Keel et al, 2000.

Have you ever:

Had an adverse reaction to TMS?

Had a seizure?	Y/N
Had an EEG?	Y/N
Had a stroke?	Y/N
Had a head injury (include neurosurgery)?	Y/N
Do you have any metal in your head (outside of the mouth,) such as shrapnel, surgical clips, or fragments from welding or metalwork?	Y/N
Do you have any implanted devices such as cardiac pacemakers, medical pumps, or intracardiac lines?	Y/N
Do you suffer from frequent or severe headaches?	Y/N
Have you ever had any other brain-related condition?	Y/N
Have you ever had any illness that caused brain injury?	Y/N
Are you taking any medications?	Y/N
Does anyone in your family have epilepsy?	Y/N
Do you need further explanation of TMS and its associated risks?	Y/N
Have you drunk more than 3 units of alcohol in the last 24 hours?	Y/N

Edinburgh Handedness Inventory (revised)

Please mark the box that best describes which hand you use for the activity in question

	Always Left	Usually Left	No Preference	Usually Right	Always Right
Writing					
Throwing					
Scissors					
Toothbrush					
Knife (without fork)					
Spoon					
Match (when striking)					
Computer mouse					

Appendix B2: Strength and weaknesses of TMS techniques

Low- and high-frequency rTMS bear quite different safety risks.

Weaknesses

Seven patients have been reported who suffered from seizures following *single pulse TMS*. However, seizures are rare and occur mainly in patient populations (Fauth, Meyer, Prosiegel, Zihl, & Conrad, 1992; Homberg & Netz, 1989; Hufnagel, Elger, Klingmuller, Zierz, & Kramer, 1990; Kandler, 1990); Three episodes were unpublished but occurred in adult patients with other pre-existing brain lesions, which may have caused the seizures (for a review see Garvey & Gilbert, 2004).

High-frequency rTMS has been known to induce seizures at high stimulus intensities and rates. However, there have been only 5 reported rTMS induced seizures in healthy participants world-wide, and these occurred with high-frequency repetition rates, short inter-train intervals, and stimulus intensities that exceeded the values in the proposed project and current guidelines. Four of these five seizures occurred in volunteers studied at the National Institute of Neurological Disorders and Stroke during the program of clinical development of rTMS as a technique (Wassermann, 1998). All seizures were single events and were not followed by any other seizures. Despite a large increase in use of TMS in the last five years, there have been no seizures reported since new guidelines for the use of rTMS were published in 1998 (Gilbert, et al., 2004; Tassinari, Cincotta, Zaccara, & Michelucci, 2003). TMS has recently been approved by the Federal Drug Administration in the United States as a treatment for depression and aphasia.

During TMS there is an associated loud clicking sound from the coil. The peak sound pressure is approximately 120-130dB 10cm from the coil. Most sound energy is in the frequency range 2-7 KHz. In order to avoid any discomfort, appropriate hearing protection (foam ear plugs) can be provided for both the investigator and the subjects.

Some contraction of scalp muscles can be experienced with single-pulse TMS and rTMS, which may be associated with minor discomfort. This may lead to a mild headache, which is assumed to be caused by activation of the scalp and neck muscles.

The strong magnetic field can affect electrical equipment and ferrous metal implants.

Three subjects receiving rapid rate repetitive TMS suffered from temporary auditory threshold shifts, but no permanent hearing loss was documented (Garvey & Gilbert, 2004).

It may cause discomfort or even pain: Loud clicking sound is produced by the stimulating coil due to the rapid deformation of the TMS coil which is enhanced with stimulator intensity. Hearing protection can be offered to prevent discomfort. The coil can overheat and in severe cases, can cause skin burns. Some participants may find that the rTMS causes a mild headache. This may be due to the contraction of the scalp and neck muscles caused by the magnetic pulses.

TMS alone cannot localize specific regions (see e.g. Wagner, Rushmore, Eden, & Valero-Cabre, 2009, for a review). Different angles of coil to head might stimulate different regions. Methods to make localization more precise are available but expensive (e.g. LORETA, MiniBIRD).

Strengths

TMS or rTMS as a non-invasive mapping technique allows researchers to see what regions of the brain are activated when a subject performs a certain task. It can help demonstrate causality in research: If a specific region shows fMRI activity during a specific task this is not proof that those regions are actually used for the task, only that this region is associated with a task. (r)TMS can then reveal some evidence if the region is used during a specific task or not e.g. if the magnetic pulse significantly slows down reaction times or accuracy.

TMS can be used as a complimentary tool with other non-invasive correlational techniques such as PET, fMRI or EEG. The combination of any of the two methods might be the strongest approach (Mottaghy, 2006), but is very expensive and needs specialist equipment.

It is currently used in hospitals as a method for diagnosis and therapeutic treatment for patients with psychiatric disorders such as depression, and neurological disorders such as Parkinson's disease and epilepsy.

Children who were administered TMS pulses rated the experience as less pleasant than watching TV, but more pleasant than a long car journey (Garvey, Kaczynski, Becker, & Bartko, 2001).

Repetitive transcranial magnetic stimulation has no known long term adverse effects.

No known seizures have ever been recorded in studies using low frequency rTMS.

Like single-pulse or paired-pulse TMS, low-frequency rTMS can be employed both in volunteers and patients with neurological diseases without risks (Tassinari, et al., 2003).

Low frequency rTMS reduces cortical excitability, and as such is currently being investigated as a potential treatment for epilepsy (Tassinari, et al., 2003).

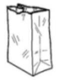
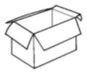
Low frequency rTMS is widely used as a therapeutic intervention in depression and other psychiatric and neurological disorders, with patients typically receiving 10-15 daily sessions in which 600-1000 pulses are administered over 10-15 minutes.

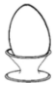
There have been no incidences of TMS induced seizure reported using low-frequency rTMS or single pulse TMS in either therapeutic settings with patient participants or research settings with healthy volunteers.

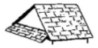
Guidelines for maximum safety are available.

Appendix C1: Experimental material for the English/German tasks

Rhyme game

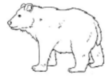
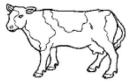
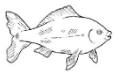
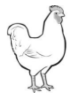
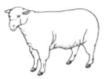
Pictures for Picture Naming	Word English	word length Female	Male	CELEX Cob	Nb Syll esyll	Nb Car echar	NbPhon	AoA	Word German	word length Female	Male	CELEX MANN	NbSyll gsyll	NbCar gchar	NbPhon	AoA
	bag	0,55	0,50	1098	1	3	3	45	Sack	0,41	0,57	102	1	4	3	26
	ball	0,63	0,59	1664	1	4	3	41	Ball	0,51	0,39	333	1	4	3	17
	bath	0,65	0,52	796	1	4	3	42	Bad	0,60	0,46	821	1	3	3	25
	bed	0,57	0,39	4376	1	3	3	42	Bett	0,35	0,54	476	1	4	3	21
	boat	0,55	0,54	1000	1	4	3	44	Boot	0,48	0,50	86	1	4	3	26
	book	0,57	0,48	4832	1	4	3	41	Buch	0,50	0,54	591	1	4	3	27
	box	0,67	0,70	0	1	3	3	45	Box	0,43	0,52	15	1	3	3	25
	boy	0,54	0,48	3720	1	3	3	44	Bub	0,52	0,46	15	1	3	3	19
	bus	0,61	0,55	1155	1	3	3	44	Bus	0,45	0,50	42	1	3	3	23
	bush	0,57	0,57	751	1	4	3	48	Busch	0,45	0,43	41	1	5	3	29
	case	0,68	0,67	6866	1	4	3	51	Fach	0,52	0,43	92	1	4	3	32
	chin	0,52	0,61	457	1	4	3	48	Kinn	0,48	0,46	66	1	4	3	24

	comb	0,65	0,65	76	1	4	3	48	Kamm	0,54	0,46	32	1	4	3	22
	cook	0,52	0,44	266	1	4	3	45	Koch	0,45	0,42	51	1	4	3	35
	door	0,59	0,48	5891	1	4	3	42	Tür	0,50	0,48	xxx	1	3	3	22
	ear	0,48	0,54	751	1	3	2	42	Ohr	0,47	0,41	149	1	3	2	22
	egg	0,44	0,41	661	1	3	2	45	Ei	0,48	0,46	55	1	2	2	20
	foot	0,63	0,66	1753	1	4	3	45	Fuss	0,58	0,61	99	1	3	3	34
	hair	0,57	0,63	3420	1	4	3	43	Haar	0,48	0,44	247	1	5	3	29
	hat	0,57	0,57	950	1	3	3	43	Hut	0,50	0,43	84	1	3	3	28
	hay	0,52	0,48	266	1	3	3	49	Heu	0,47	0,37	29	1	3	2	29
	head	0,44	0,43	4005	1	4	3	44	Kopf	0,43	0,54	1195	1	4	3	28
	hole	0,63	0,59	1015	1	4	3	49	Loch	0,48	0,61	56	1	4	3	23
	house	0,68	0,63	8601	1	5	3	40	Haus	0,52	0,70	620	1	4	3	27
	ice	0,67	0,65	934	1	3	2	46	Eis	0,54	0,59	53	1	3	3	30
	kiss	0,68	0,59	230	1	4	3	44	Kuss	0,50	0,55	xxx	1	4	3	31
	lake	0,59	0,63	718	1	4	3	49	See	0,56	0,41	171	1	3	2	22
	leg	0,54	0,50	1137	1	3	3	44	Bein	0,56	0,46	122	1	4	3	26
	man	0,65	0,65	17486	1	3	3	44	Mann	0,52	0,48	2883	1	4	3	33

	net	0,61	0,63	290	1	3	3	52	Netz	0,50	0,59	89	1	4	3	23
	pot	0,50	0,52	416	1	3	3	47	Topf	0,52	0,54	40	1	4	3	24
	rag	0,63	0,52	101	1	3	3	51	Tuch	0,48	0,59	17	1	4	3	25
	rice	0,74	0,78	488	1	4	3	49	Reis	0,65	0,61	12	1	4	3	27
	ring	0,61	0,62	628	1	4	3	48	Ring	0,50	0,44	106	1	4	3	29
	roof	0,65	0,69	831	1	4	3	52	Dach	0,39	0,50	146	1	4	3	28
	rope	0,63	0,63	552	1	4	3	52	Seil	0,60	0,79	35	1	4	3	22
	sea	0,66	0,65	2872	1	3	2	51	Meer	0,56	0,50	334	1	4	3	30
	ship	0,59	0,58	793	1	4	3	46	Schiff	0,45	0,59	308	1	6	3	27
	shoe	0,67	0,60	249	1	4	2	43	Schuh	0,58	0,46	31	1	5	2	26
	song	0,65	0,76	687	1	4	3	46	Lied	0,58	0,57	136	1	4	3	26
	tea	0,59	0,60	1589	1	3	2	47	Tee	0,50	0,44	79	1	3	2	27
	toe	0,59	0,60	10	1	3	2	50	Zeh	0,56	0,48	9	1	3	2	24
	tooth	0,68	0,60	233	1	5	3	48	Zahn	0,65	0,57	12	1	4	3	26
	watch	0,74	0,69	662	1	5	3	49	Uhr	0,54	0,41	4337	1	3	2	24
	wheel	0,57	0,63	494	1	5	3	51	Rad	0,58	0,54	151	1	3	3	30
	zoo	0,65	0,65	156	1	3	2	46	Zoo	0,56	0,46	75	1	3	2	25
		0,60	0,58	1867	1,00	3,67	2,83	46		0,51	0,51	313,98	1,00	3,72	2,80	25

Note: word length = duration of acoustic stimuli; CELEX Cob = Frequency; NbSyll = Number of Syllable; esyll = English syllables; gsyll = German syllables; NbCar = Number of Characters/Letters; echar = English characters; gchar = German characters; AoA = Age of Acquisition

Animal Game

Pictures for Picture Naming	Word English	word length Female	Male	CELEX Cob	Nb Syll esyll	Nb Car echar	Nb Phon	AoA	Word German	word length Female	Male	CELEX MANN	Nb Syll gsyll	Nb Car gchar	Nb Phon	AoA
	bear	0,50	0,50	102	1	4	3	43	Bär	0,48	0,38	xxx	1	3	3	21
	cow	0,60	0,60	395	1	3	3	45	Kuh	0,55	0,46	136	1	3	2	21
	fish	0,58	0,65	1438	1	4	3	45	Fisch	0,53	0,43	99	1	5	3	23
	hen	0,41	0,41	100	1	3	3	46	Huhn	0,60	0,50	14	1	4	3	29
	mouse	0,67	0,79	146	1	5	3	46	Maus	0,62	0,55	28	1	4	3	22
	sheep	0,65	0,72	359	1	5	3	46	Schaf	0,74	0,58	11	1	5	3	24
	whale	0,58	0,53	104	1	5	3	48	Wal	0,50	0,43	2	1	3	3	31
		0,57	0,60	377,71	1,00	4,14	3,00	45,49		0,58	0,48	41,43	1,00	3,86	2,86	24,36

Note: word length = duration of acoustic stimuli; CELEX Cob = Frequency; NbSyll = Number of Syllable; esyll = English syllables; gsyll = German syllables; NbCar = Number of Characters/Letters; echar = English characters; gchar = German characters; AoA = Age of Acquisition

Appendix C2: Parental Consent Form

Mag. Kathrin Klingebiel
DPhil candidate, University of Sussex, UK
K.A.M.Klingebiel@sussex.ac.uk

Mobile: 07527154189
Office: 01273 876649

Dear parents/guardians,

In the upcoming months a study on the topic „bilingualism, memory and vocabulary acquisition" will be conducted at your child's school. It will be evaluated if and how verbal short term memory for serial order is related to vocabulary knowledge. So far, we only know that the verbal short term memory in general is related to language acquisition, but no details are yet known.

The results of this study will help to develop profound language trainings to make language acquisition for both, children and adults, easier. Also, they will resolve important neurological issues: For instance they will help to locate the route of acquired language disorders (e.g. after an insult or accident with brain damage) and hence will help to develop specific training methods.

In the upcoming study, each child will solve tasks on the topic language and memory with me. All tasks will be presented in a playful and fun way.

If you are willing to let your child take part in the study, please fill out the parental consent form and hand it back to your child's teacher.

Thank you very much for your support, if you have any further questions do not hesitate to contact me via phone (07527154189) or Email K.A.M.Klingebiel@sussex.ac.uk!

Warm regards,

Kathrin Klingebiel

Parental/Guardian consent form

All information on this sheet is highly confidential and will be evaluated anonymous!
Your child can drop out of the study at any time, also during tasks.

Child's Name: ____

School: ______________________________________ **Class:** ______________

Date of birth: __________________________ **Boy** □ **Girl** □

You child can take part in the study if he/she (please tick):

- □ speaks English and learns French;
- □ has/had normal language development;
- □ has/had no learning disabilities (e.g. dyslexia);
- □ has no neurological impairments (e.g. epilepsy);
- □ has normal or corrected-to-normal auditory and visual acuity.

Parent/Guardian:

Name: ……………………………………………………………………………………

Signature: ……………………………………………………………………………………………

Date and Place: ……………………………………………………………………………………………

Please hand the filled-in consent form back to your child's teacher!

Appendix C3: Parental Questionnaire

Parental questionnaire

Dear parents!
The study „bilingualism, memory and language acquisition" involves this parental questionnaire. Please answer the following questions. All information on this questionnaire is **highly confidential** and will remain **anonymous**.
Thank you very much in advance for your co-operation!
All the best,

Mag. Kathrin Klingebiel

General questions regarding your child

1	ID Number	
2	Date of birth	
3	School	
4	Class	

5	How old was your child when it started to learn **German**?	☐ 0 – 3 years ☐ 4 – 6 years ☐ 7 – 10 years ☐ after 11 years
6	How old was your child when it started to learn **English**?	☐ 0 – 3 years ☐ 4 – 6 years ☐ 7 – 10 years ☐ after 11 years
7	Does your child speak any other language than German or English fluently? If yes, which one(s)?	Language A: ____________________ Language B: ____________________
7a	If the answer to question 7 was yes, how old was your child when it started to learn **language A**?	☐ 0 – 3 years ☐ 4 – 6 years ☐ 7 – 10 years ☐ after 11 years
7b	If the answer to question 7 was yes, how old was your child when it started to learn **language B**?	☐ 0 – 3 years ☐ 4 – 6 years ☐ 7 – 10 years ☐ after 11 years

8	How many years did your child live in an **English** speaking country?	_______ years
9	Haw many years did your child live in a **German** speaking country?	_______ years
10	How many years did your child live in a country with another language? What was the national language of that country?: ___________________ Which language(s) did your child speak there? ____	_______ years

11	How many hours per day does your child approximately spend **neither at school nor at home**?	_______ hours (E.g. in a sport club, etc.)

12	Which language does your child use in this environment?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other languages: _________________	☐	☐	☐	☐	☐

13	How many hours per day does your child approximately spend in **school**?	_______hours

14	Which language(s) does your child use at school?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other languages: _________________	☐	☐	☐	☐	☐

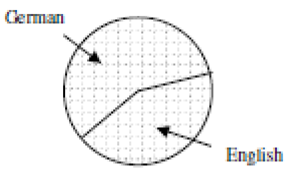
15	How many hours per day does your child approximately spend at **home**?	_______hours

16	Which language(s) does your child use at home?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other languages: _________________	☐	☐	☐	☐	☐

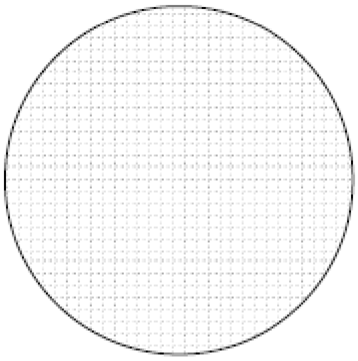
Language circle

17	How much time does your child spend using a certain language during one week? (Circle represents one week)

Example:



Your answer:



Family

18	Family status of the parents: ☐ single ☐ married ☐separated/divorced ☐ widowed ☐ permanent relationship	
19	With whom does the child live? (multiple answers permitted)	☐ Mother ☐ Father ☐ Siblings ☐ Other:______________
20	How many people live in your home?	1 2 3 4 5 6 7 8 9 10

For the following questions:

21	Please name the two **adults** that your child is attached to the closest and with whom he/she spends most of his/her time (other then in school):
Person A (only one answer permitted)	☐ Mother ☐ Father ☐ Other:______________
Person B (only one answer permitted)	☐ Mother ☐ Father ☐ Other:______________

What is your **native language** (the language that you learnt from birth)?

22	Person A	☐ German	☐ English	☐ Other:____________________
23	Person B	☐ German	☐ English	☐ Other:____________________

Please judge your **German** knowledge

24	Person A	☐ fluid	☐ intermediate	☐ beginner	☐ not at all
25	Person B	☐ fluid	☐ intermediate	☐ beginner	☐ not at all

Please judge your **English** knowledge

26	Person A	☐ fluid	☐ intermediate	☐ beginner	☐ not at all
27	Person B	☐ fluid	☐ intermediate	☐ beginner	☐ not at all

28 In which language does **Person A** talk to the child?

	always	often	sometimes	seldom	never
German	☐	☐	☐	☐	☐
English	☐	☐	☐	☐	☐
Other language: ____________________	☐	☐	☐	☐	☐

29 In which language does the **Person B** talk to the child?

	always	often	sometimes	seldom	never
German	☐	☐	☐	☐	☐
English	☐	☐	☐	☐	☐
Other language: ____________________	☐	☐	☐	☐	☐

Siblings

30	How many siblings (including stepsiblings) does the child have?	0	1	2	3	4	5	6	7
31	How many are boys?	0	1	2	3	4	5	6	7
32	How many are girls?	0	1	2	3	4	5	6	7
33	In which birth position is the child?		1	2	3	4	5	6	7
34	How many siblings live in the same home?	0	1	2	3	4	5	6	7

Only answer if you child has siblings:

35	Which language do the siblings use to communicate?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other language: ____________________	☐	☐	☐	☐	☐

Friendships

36	How many hours per day does your child spend with his/her friends outside of school?	_______ hours

37	In which language does your child speak with his/her friends?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other language: __________________	☐	☐	☐	☐	☐

Free time

38	How often does your child read books?	☐ every day	☐ several times per week	☐ once per week	☐ less frequently	☐ never

39	In which language are the books written that your child reads?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other language: __________________	☐	☐	☐	☐	☐

40	How often does your child watch TV?	☐ every day	☐ several times per week	☐ once per week	☐ less frequently	☐ never

41	In which language are the programs that your child watches on TV?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other language: ____________________	☐	☐	☐	☐	☐

42	How often does your child listen to audio books?	☐ every day	☐ several times per week	☐ once per week	☐ less frequently	☐ never

43	In which language does your child listen to audio books?				
	always	often	sometimes	seldom	never
English	☐	☐	☐	☐	☐
German	☐	☐	☐	☐	☐
Other language: ______________________	☐	☐	☐	☐	☐

General questions

How old are you?

44	Person A	__________ years
45	Person B	__________ years

What is your highest level of education?

46	Person A	☐ secondary school / middle school	☐ apprenticeship / vocational school	☐ High school	☐ University / Academy
47	Person B	☐ secondary school / middle school	☐ apprenticeship / vocational school	☐ High school	☐ University / Academy

What is your current profession?

48	Person A	☐ manager, self-employed	☐ employee, appointee	☐ worker	☐ housewife, pension, maternity leave	☐ Other: ___________
49	Person B	☐ manager, self-employed	☐ employee, appointee	☐ worker	☐ houseman, pension, paternity leave	☐ Other: ___________

How many hours per week are you employed?

50	Person A	☐ full-time	☐ half-time	☐ by the hour	☐ not at all
51	Person B	☐ full-time	☐ half-time	☐ by the hour	☐ not at all

How much is the approximate monthly family income?

52	☐ up to 1090 Euro	☐ up to 1817 Euro	☐ up to 2544 Euro	☐ up to 3270 Euro
53	☐ up to 3997 Euro	☐ over 3997 Euro		

Who filled in this questionnaire?	☐ Person A ☐ Person B

Thank you very much for your co-operation!

If you have any further questions do not hesitate to contact me.
All the best,
Kathrin Klingebiel

Mag. Kathrin Klingebiel
DPhil candidate, University of Sussex, UK
K.A.M.Klingebiel@sussex.ac.uk

Contact details for Austria:
Mobile: 0680 217 23 34
Tel.: 01 889 46 88

Appendix C4: Parental Questionnaire Results

Language knowledge: According to their parents 88.9% (N=80) of children were between 0 and 3 years of age when they started to learn German (6 children only learned German between 4 – 6 years) and 74.4% (N=67) were between 0 and 3 years of age when they started to learn English (19 only learned English between 4 – 6 years). Three children spoke English more fluently than German, and two of them were trilingual from birth. Children had lived on average about one year in an English speaking country (range: 0 - 7.5 years) and eight years in a German speaking country (range 0.5 – 10 years).

Language environment: Children spent on average two hours neither at school nor at home. In this environment they used German (84.4%) and English (25.6%) always or often (other options: sometimes, seldom, never). They spent about 5.5 hours in school and there they speak German (90.1%) and English (83.4%) always or often (other options: sometimes, seldom, never). At home children speak German (78.8%) and English (56.7%) always or often (other options: sometimes, seldom, never). When parents were asked which the child was most attached to (A or B), 95.6% of all parents named the mother as person A and 80% the father as person B. Other persons named were grandmother and teacher. Person A's native language was German (56.7%), English (28.9%) and another native language (10%). Person B's native language is German (62.2%), English (26.7%) and another native language (4.4%). Mostly, Person A's German knowledge is native/fluent (67.8%) or intermediate (25.6%) (Beginners: 2.2%), Person B's is native/fluent (67.8%) or intermediate (18.9%), only 4.4% are beginners. English knowledge in Person A is native/fluent (64.4%) or intermediate (27.8%) (Beginners: 2.2%) and Person B's native/fluent (61.1%) or intermediate (25.6%) (Beginners: 3.3%). Person A speaks to the bilingual child German 54.4% of the time always or often and 46.6% English always or often (other options: sometimes, seldom, never). Person B speaks to the bilingual child German 64.5% always or often and 35.5% English always or often (other options: sometimes, seldom, never). Person A was on average 40.4 years old (range 32-57), Person B 42.6 (range 25 – 61). More than 67.5% of Persons A and B have university education (Person A: 23.3%

high school, 1.1% apprenticeship, 2.2% secondary school; Person B: 22.9% high school, 6.7% apprenticeship, 2.2% secondary school). 35.6% of person A work full time, 25.6% half-time, 15.6% by the hour and 14.4% not at all. They are 26.7/% managers or self employed, 36.7% employees, 3.3% workers, 21.2% housewives and 5% have other jobs. Person B works 80% full time, 6.7% half-time, 1.1% by the hour and 1.1% not at all. 55.6% are managers or self-employed, 30% employees, 3.3% housewives and 3.3% other jobs. The questionnaire was filled in 82.2% by person A.

Hobbies: In their free time bilingual children read books (46.7% every day, 33.3% several times per week, 12.2% once per week, 2.2% less frequent) in German (68.9% always or often) and English (72.2% always or often), watch TV (23.3% every day, 43.3% several times per week, 16.7% once per week, 11.1% less frequent) in German (76.6% always or often) and English (41.1% always or often) or listen to audio books (4.4% every day, 15.6% several times per week, 7.8% once per week, 66.6% less frequent) in German (41.1% always or often) and English (23.3% always or often).

Family situation: The family status of parents was married (74.4%), separated or divorced (8.9%), single (5.6%), and live in a permanent relationship (5.6%). 64.4% of the children live with their mother, father and siblings, 20% with both of their parents and 10% with their mother or their mother and siblings. Bilingual children have on average one sibling (range 0 – 5, SD 0.871). With their sibling, they speak 57.8% of the time German always or often and 28.9% English always or often. Children spend on average 2.5 hours with their friends outside of school. 88.9% speak German always or often and 36.7% English always or often.

Appendix C5: Teacher Questionnaire

Dear Teacher,

To participate in a study on *memory and bilingualism in children*, we are currently looking for bilingual children who speak German and English.
Please help me to identify those children in your class by filling in this questionnaire.

Your name: ____

Schol: ____

Grade: ____________

First name and first letter of the last name of each child	Questions about each student
	Since birth he/she is learning ❑ English & German ❑ German ❑ English ❑ another language: ______________ How well does the child speak German? ❑ fluent ❑ very well ❑ quite well ❑ a little ❑ not at all How well does the child speak English? ❑ fluent ❑ very well ❑ quite well ❑ a little ❑ not at all
	Since birth he/she is learning ❑ English & German ❑ German ❑ English ❑ another language: ______________ How well does the child speak German? ❑ fluent ❑ very well ❑ quite well ❑ a little ❑ not at all How well does the child speak English? ❑ fluent ❑ very well ❑ quite well ❑ a little ❑ not at all
…	…

Thank you very much for your support!

For further questions please do not hesitate to contact me at any time!
Best regards,

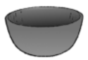
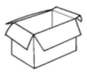
Kathrin Klingebiel

Mag. Kathrin Klingebiel
DPhil candidate, University of Sussex, UK
K.A.M.Klingebiel@sussex.ac.uk

Contact in Austria:
Mobile: 0680 217 23 34
Phone: 01 889 46 88

Appendix C6: Experimental material for English/French tasks

Rhyme game

Pictures for Picture Naming	Word English	word length Female	Male	CELEX Cob	NbSyll esyll	NbCar echar	NbPhon ephon	Word Female	word length Male	Female	NOVLEX MANN	NbSyll fsyll	NbCar fchar	NbPhon fphon
	bag	0,55	0,65	1098	1	3	3	sac	0,62	0,50	33800	1	3	3
	ball	0,50	0,67	1664	1	4	3	balle	0,62	0,60	12615	1	5	3
	bath	0,67	0,72	796	1	4	3	bain	0,36	0,46	8569	1	4	2
	bay	0,50	0,65	528	1	3	2	jus	0,43	0,48	2380	1	3	2
	bowl	0,55	0,74	461	1	4	3	bol	0,50	0,50	3332	1	3	3
	box	0,65	0,89	0	1	3	3	boîte	0,65	0,58	24754	1	5	4
	bus	0,58	0,77	1155	1	3	3	bus	0,58	0,62	1666	1	3	3
	cage	0,67	0,96	225	1	4	3	cage	0,60	0,53	13091	1	4	3

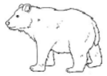
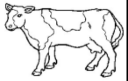
	chain	0,60	0,82	585	1	5	3	chaîne	0,58	0,60	6426	1	6	3
	chair	0,55	0,74	1840	1	5	3	chaise	0,60	0,70	10473	1	6	3
	coin	0,58	0,82	132	1	4	3	coin	0,46	0,41	29277	1	4	3
	cup	0,43	0,62	1067	1	3	3	tasse	0,55	0,53	4998	1	5	3
	day	0,50	0,67	13729	1	3	2	jour	0,65	0,50	181377	1	4	3
	edge	0,58	0,67	1356	1	4	3	tour	0,55	0,50	42607	1	4	3
	egg	0,46	0,60	661	1	3	2	oeuf	0,46	0,55	30229	1	4	2
	foot	0,50	0,67	1753	1	4	3	jambe	0,58	0,62	27135	1	5	3
	head	0,46	0,53	4005	1	4	3	tête	0,53	0,43	123536	1	4	3
	heap	0,41	0,72	180	1	4	3	vase	0,50	0,60	8092	1	4	3
	hut	0,58	0,65	396	1	3	3	hotte	0,48	0,43	1666	1	5	3
	king	0,50	0,67	1598	1	4	3	roi	0,41	0,34	119728	1	3	3
	kiss	0,62	0,67	230	1	4	3	bec	0,53	0,50	11663	1	3	3

	lamp	0,55	0,79	381	1	4	3	lamp	0,53	0,60	4998	1	5	4
	leaf	0,55	0,70	267	1	4	3	feuille	0,65	0,53	29039	1	7	3
	man	0,55	0,79	17486	1	3	3	homme	0,41	0,46	117109	1	5	2
	moon	0,50	0,79	951	1	4	3	lune	0,60	0,55	24992	1	4	3
	mouth	0,62	0,74	2411	1	5	3	bouche	1,03	0,62	37608	1	6	3
	neck	0,57	0,74	1299	1	4	3	cou	0,31	0,34	19994	1	3	2
	night	0,65	0,79	7671	1	5	3	nuit	0,50	0,48	91878	1	4	3
	nose	0,74	0,89	1307	1	4	3	nez	0,43	0,46	41416	1	3	2
	nut	0,67	0,72	0	1	3	3	noix	0,48	0,53	2618	1	4	3
	page	0,65	0,91	1074	1	4	3	page	0,60	0,55	5236	1	4	3
	pipe	0,55	0,70	394	1	4	3	pipe	0,41	0,60	1190	1	4	3
	pot	0,58	0,67	416	1	3	3	pot	0,29	0,29	17376	1	3	2
	rice	0,60	0,86	488	1	4	3	riz	0,36	0,43	2142	1	3	2

	ring	0,48	0,79	628	1	4	3	bague	0,65	0,55	2142	1	5	3
	road	0,62	0,82	3791	1	4	3	rue	0,43	0,48	28087	1	3	2
	rock	0,58	0,74	1398	1	4	3	salle	0,65	0,62	16900	1	5	3
	room	0,55	0,77	8249	1	4	3	pièce	0,60	0,38	29753	1	5	4
	rose	0,77	0,94	110	1	4	3	rose	0,58	0,60	19042	1	4	3
	route	0,50	0,70	710	1	5	3	route	0,53	0,60	35942	1	5	3
	sea	0,70	0,79	2872	1	3	2	lac	0,60	0,55	12853	1	3	3
	sky	0,70	0,96	1380	1	3	3	ciel	0,67	0,65	37132	1	4	4
	son	0,55	0,79	2858	1	3	3	fils	0,58	0,62	37846	1	4	3
	soup	0,55	0,82	362	1	4	3	soupe	0,62	0,55	8569	1	5	3
	tea	0,55	0,62	1589	1	3	2	thé	0,31	0,31	5236	1	3	2
	tooth	0,58	0,72	233	1	5	3	dent	0,46	0,46	41654	1	4	2
	wall	0,58	0,82	2374	1	4	3	mur	0,58	0,65	28801	1	3	3
	year	0,55	0,74	9105	1	4	3	roc	0,46	0,50	1190	1	3	3
		0,56	0,74	2067,90	0,98	3,72	2,84		0,52	0,51	27977,42	0,98	4,04	2,80

Note: Word length = duration of acoustic stimuli; CELEX Cob = Frequency; NbSyll = Number of Syllable; esyll = English syllables; fsyll = French syllables; NbCar = Number of Characters/Letters; echar = English characters; fchar = French characters

Animal Game

Pictures for Picture Naming	Word	word length		CELEX	NbSyll	NbCar	NbPho	Word	word length		NOVLEX	NbSyll	NbCar	NbPhon
	English	Female	Male	Cob	esyll	echar	ephon	French	F	M	Freq100	fsyll	fchar	fphon
	bear	0,48	0,58	227	1	4	3	ours	0,60	0,62	63553	1	4	3
	cat	0,53	0,84	739	1	3	3	chat	0,43	0,50	90926	1	4	2
	cow	0,55	0,77	395	1	3	3	vache	0,55	0,53	13091	1	5	3
	dog	0,46	0,53	1233	1	3	3	chien	0,50	0,60	74264	1	5	3
	hen	0,58	0,67	100	1	3	3	poule	0,43	0,43	29515	1	5	3
	lion	0,60	0,84	152	1	4	3	lion	0,53	0,50	21184	1	4	3
	rat	0,55	0,82	156	1	3	3	rat	0,38	0,43	16900	1	3	2
		0,53	0,72	428,86	1,00	3,29	3,00		0,49	0,52	44204	1,00	4,29	2,71

Note: Word length = duration of acoustic stimuli; CELEX Cob = Frequency; NbSyll = Number of Syllable; esyll = English syllables; fsyll = French syllables; NbCar = Number of Characters/Letters; echar = English characters; fchar = French characters

Appendix C7: Task Instructions

Instructions Picture Naming

> *In this game, please always name the picture that you see on the screen. If you don't know the name you can skip the picture by saying "skip". Ready?*

If the child's motivation dropped it was encouraged (*you can do it, good job*, *almost done,* etc.).

Instructions Rhyme Task

First Block (without headphones):

> *First, you will hear two words followed by a peep. After the peep you will hear another word. You should choose if the word AFTER the peep rhymes with one of the words before the peep. Press the red, sad smiley for NO and the green, happy smiley for YES. Press enter to start!*

After the first Block:

> *Great! Well done! You have just finished the first block! Now one word is added, so you will hear three words before the peep. Then you will reach the next block and another word will be added. Are you ready? Ok. Then you can now put on the headphones. Everything alright? Ok! Then let's start!*

If the child's motivation dropped it was encouraged (*you can do it, good job*, *almost done,* etc.).

Instructions Animal Game

First Block (without headphones):

> *In this game you will listen to two animal names. Then you will hear a beep and you will see pictures of the animals. Click on the correct order in which you heard the animal names. So if you heard for example duck and fish then you click first on duck and then on fish. Ok? Ok, then let's start!*

After the first Block:

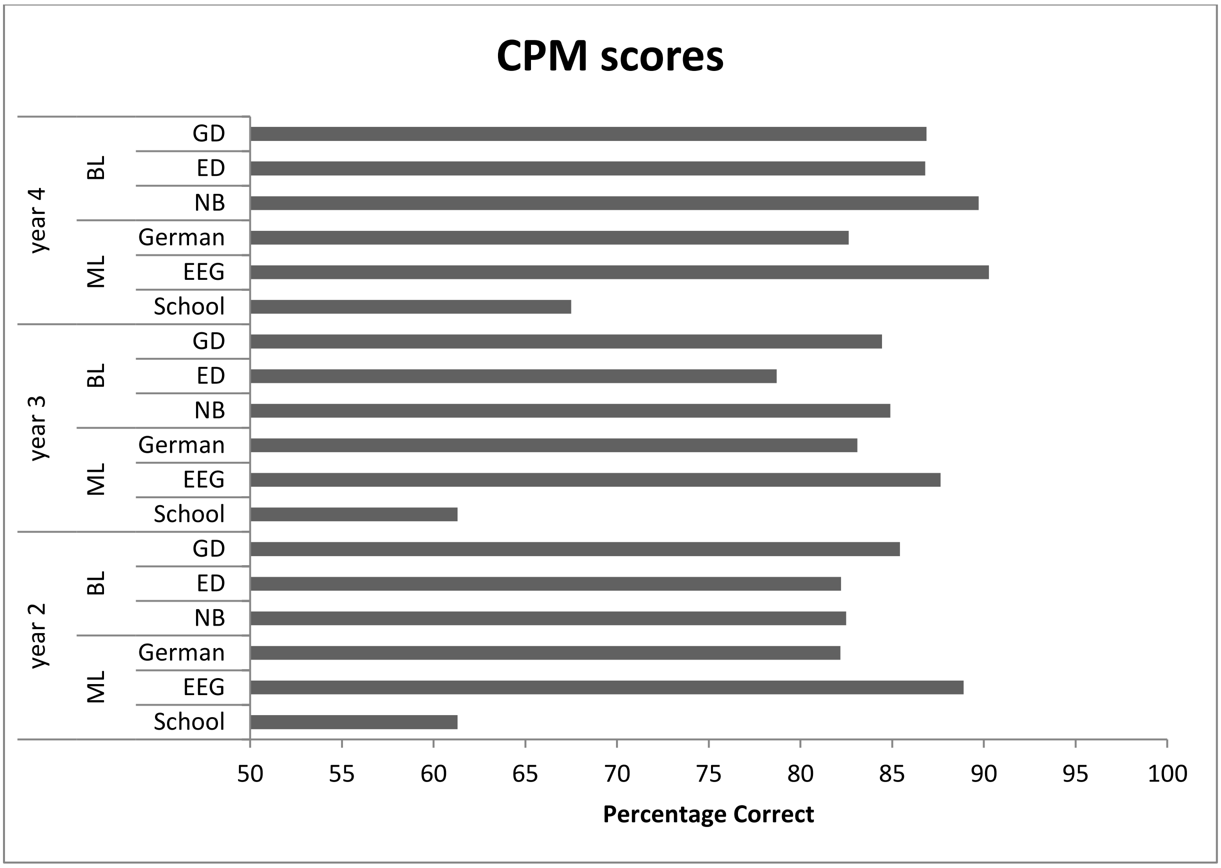
> *Great! Well done! You have just finished the first block! Now one animal is added, so you will hear three animal names and then you will see three pictures of the animals. Click on the pictures in the correct order. Then you will reach the next block and another animal will be added. Are you ready? Ok. Then you can now put on the headphones. Everything alright? Ok! Then let's start!*

If the child's motivation dropped it was encouraged (*you can do it, good job*, *almost done,* etc.).

Appendix C8: Comparison of non-verbal reasoning skills

The difference in non-verbal reasoning skills between bilingual children and the English monolingual group is very likely due to different test-settings: The English ML children were presented with the CPM administered as a class-test while BL children were tested face-to-face. In face-to-face settings children have less disturbing sources.

When looking at CPM scores of English ML children who took part in the EEG study (see Chapter 2; tested in face-to-face settings like BL children) no differences could be found.



Note: ML = Monolinguals; BL = Bilinguals; GD=German dominant bilinguals, ED= English dominant bilinguals, NB=Native bilinguals, German = German monolingual children, EEG= English monolingual children from EEG study, School= English monolinguals from school sample

Appendix D1: Consent form Monolingual Adults Study

<u>Information for participants</u>

The Purpose of the Experiment

Help to discover what memory components we need to learn a language.

What you will be required to do

In recent years many studies have shown that vocabulary acquisition processes and aspects of verbal short-term memory are closely related to each other. Yet, only few studies have investigated vocabulary learning in monolingual speakers while taking into account the apparent crucial differentiation between item and order verbal STM. This study aims to investigate the possible differential influences of item and order STM on language acquisition in monolingual English speaking adults. Participants will attend a serial order reconstruction task (remember 4 to 9 animals and place them in correct order) to test for order STM skills and a rhyme probe recognition task (remember 4 to 9 words and judge if one of them rhymed with a target word) as item STM task. A picture-nonword learning task will then test participants' language learning skills. In addition, English vocabulary and nonverbal reasoning skills will also be evaluated.

Precautions

You should *not* take part if you:

1. do not speak English as your first language
2. do speak more than one language fluently

On completion of the study you will receive 8 GBP for 90 minutes of your time.

Taking part is entirely voluntary and confidential.

Volunteer Consent Form

I have read and had explained to me details of the above study. I am aware that I have the right to withdraw from the experiment at any time. I fully understand the nature and purpose of the study and give my consent to participate.

Name: ______________________________

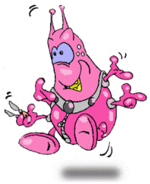
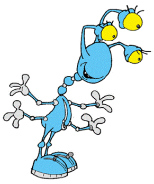
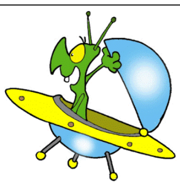
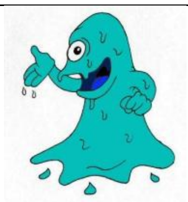
Signed: ______________________________

Date: ___ / ___ / __

Appendix D2: Learning Task Stimuli - Monolingual Adults Study

Non-word learning task stimuli list for ML adults.

Green = Czech based non-words; Blue = English based non-words

Part A			Part B	
	/kɛm-tzɛl/			/tər –‘kwɔr /
	/nʌl –‘sɪg /			/lʌt-kʌʃ/
	/tʃɪt-kɔn/			/pəs-’kʌm /
	/təl –‘pɪs /			/tel-kɔs/
	/nik-tʃiʃ/			/win-bɪ’t/
	/dʒən –‘dʌn /			/tʊp-nʌs/