The Determinants of Bilingual Memory Capacity

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Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy, October, 1997

Abstract

The variation in short-term memory capacity between the dominant and less-dominant languages of bilinguals has been explained in terms of a difference in the rate of subvocal rehearsal between the languages. The 11 experiments presented in this thesis examined the effect of factors other than subvocal rehearsal and word length on bilingual short-term memory processes. Experiment 1 found that the language in which bilinguals received schooling influenced memory span for Arabic numerals (e.g., 1, 2, 3, etc.), The findings of Experiments 2 and 3 showed that articulation time did not predict bilingual auditory span for digits or words, whereas Experiment 4 found that articulation time was a reliable predictor of memory span for non words. Taken together, these findings suggested the involvement of non-phonological factors, such as the strength of long-term memory representation and phonotactic knowledge in mediating the bilingual memory span effect. Experiment 5 demonstrated that cognitive demands independent of articulation influenced the processing of numerals. In addition, the finding that memory span for numerals was greater than for digit words (e.g., one, two, three, etc., Experiments 6 & 7) raised fundamental questions regarding the use of inconsistent representations of digits in previous studies of bilingual memory span. A closer examination of the numeral advantage effect (Experiments 8 & 9) suggested that this was partly mediated by a variation in the predisposition toward implicit forms of chunking between numerals and digit words. Finally, the findings of Experiments 10 and 11 suggested that when the level of bilingual fluency is low, differences in the time taken to output recall sequences is an influential factor in determining bilingual memory span. Overall, this thesis questioned the assumptions in the bilingual memory span literature that have given rise to simplistic and incomplete explanations of the factors that moderate bilingual memory span. It was concluded that a greater consideration of long-term semantic and phonotactic factors and their effect on the speed of perceptual processing, subvocal rehearsal, and output delays was necessary to provide a comprehensive account of the determinants of bilingual memory capacity.

Acknowledgements

The research presented here would not have been possible without generous measures of goodwill, interest, and support from a great number of friends, colleagues, and students: too many to attempt to name individually. A few statistics will provide some idea of the scale of the exercise. Facilities at four universities were used, over 500 subjects, speaking a range of six different languages were tested (many of them on more than one occasion), the Principals of seven elementary and secondary schools allowed access to their pupils. Financial support for Study Visits to Finland on three occasions was provided by the ERASMUS academic exchange program and the Experimental Psychology Society. The assistance of several undergraduate students in Finland and England in a range of capacities was invaluable. The collegial and financial support received from the Department of Psychology and Derby Hall at the University of Nottingham was welcomed and appreciated. Without assistance from all these quarters the pressures and difficulties involved in the undertaking of this thesis would have been magnified to an unimaginable degree.

A special note of thanks is extended to my dear friends in Finland: Professor Pekka Niemi (Åbo Akademi) whose timely visit to Nottingham in 1993 was instrumental in initiating this program of research: Dr. Jukka Hyönä, Dr. Matti Laine, and Dr. Raymond Bertram (Turku University), for much 'heated' and invigorating discussion. Dr. Terry Dolan (University of Nottingham) and Dr. Rumjahn Hoosain (University of Hong Kong) were instrumental in kindling my interest in cognitive psychology in general and bilingual memory in particular. I learned much about almost everything under the expert supervision and mentoring of Professor Geoffrey Underwood for which I am earnestly grateful. The Reverend Professor Douglas Davies encouraged me to go on to 'higher' things almost 10 years ago. He will doubtless be relieved, but not more than I, that this has ultimately been achieved. Finally, May's support and tolerance throughout these years, particularly during my research visits to Finland, was unstinting and provided in bountiful measure. To all of you, a sincere and most heartfelt: thanks, kiitos, tack, ευχαριστω, gracias, do che.

The data from Experiment 1 appeared in Chincotta, D. & Underwood, G. (1996). Mother tongue, language of schooling, and bilingual digit span. British Journal of Psychology, 87, 193-208.

The data from Experiment 2 appeared in Chincotta, D. & Underwood, G. (1997). Speech rate estimates, language of schooling, and bilingual digit span. European Journal of Cognitive Psychology, 9, 325-348.

The data from Experiment 5 appeared in Chincotta, D., Hyönä, J. & Underwood, G. (in press).Eye fixations, speech rate and bilingual digit span: Numeral reading indexes fluency not word length. Acta Psychologica.

The data from Experiments 6 & 7 appeared in Chincotta, D. & Underwood, G. (1997). Bilingual memory span advantage for Arabic numerals over digit words. British Journal of Psychology, 88, 295-310.

Part of the data from Experiments 1, 7 & 9 appeared in Chincotta, D. & Underwood, G. (1997). Digit span and articulatory suppression: A cross-linguistic comparison. European Journal of Cognitive Psychology, 9, 89-96.

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Chapter 1
Introduction

Cognitive psychology was described by Neisser (1967) as the endeavour to examine and explain human mental performance. A fundamental question addressed by this discipline is "What factors determine the capacity limits of the human information processing system?" The quest to understand the nature and mechanics of this system has excited and exercised experimental psychologists for a period of, at least, three decades. Over this time the outcome of such efforts has, doubtless, contributed toward a significant advancement in the understanding of mental processes. And yet, the reality that so many aspects of cognitive functioning are not fully comprehended is testimony to the richness and complexity of the system under scrutiny. This thesis, was also concerned with examining the capacity limitations of information processing, however, in this case the inquiry was located specifically within the context of short-term memory. More specifically, the studies presented in this thesis were concerned with the examination of variables that moderate the capacity limits of storage in immediate memory for bilinguals.

The description of the memory system under examination as a short-term or immediate memory reflects the transitory nature of the information store under examination. During the 1960s there was some debate as to whether it was necessary to assume a distinction between short- and long-term memory (e.g. Hebb, 1961, Melton, 1963). The evidence in favour of distinct yet interrelated memory stores, however, is now overwhelming (Baddeley, 1990). Some of the strongest support for the notion of distinct short-and long-term stores was found in studies of neurologically damaged patients. Amnesiacs, for example, perform normally on digit span measures despite displaying severe impairments in long-term memory learning (e.g., Baddeley & Warrington, 1970). Correspondingly, there are patients that display intact long-term memory abilities and a severely limited memory span of two items (Shallice & Warrington, 1970). It seems clear, therefore, that human memory should not be conceptualised as a single entity but as a series of interconnected storage and processing systems.

Acquiring a semblance of fluency in a second language is a exacting pursuit requiring persistence and effort. The demands are so exigent that success eludes many. It is well documented that short-term memory capacity in a second language is generally smaller relative to the mother tongue (e.g., Pimsleur, 1971): although, as will be discussed below, it has been claimed that this pattern of findings is not invariable (Ellis & Hennelly, 1980). While there are often obvious and intuitive explanations for the relationship in memory span between an individual's native and second language (e.g., Brown & Hulme, 1992), the aim of this thesis was to examine the determining factors and resource limitations of the information processing system that modulate the variation in memory performance between the languages in greater detail.

The rationale for examining the capacity limits of processing in bilinguals as opposed to the more conventional approach of investigating monolingual processing was one that required justification. At the theoretical level the investigation of bilingual information processing provided a convenient tool with which to examine the adequacy of current models of cognitive functioning in accounting for the pattern of findings when performance was specified in a second language. The application of Occam's Razor to theoretical models of information processing, thus, served as a crucial test of whether the heuristic principle of parsimony was met. The studies reported in this thesis, then, examined the factors that mediate the variation in short-term memory capacity between the dominant and less dominant languages of bilinguals.

Providing a usable definition of bilingualism is an area fraught with complexity that has exercised many minds. Definitions of bilingualism range from the notion of 'incipient-bilingualism' (Diebold, 1964), where a knowledge of a few words in another language satisfies the criterion, to the more stringent condition of achieving native-like control of two languages (Bloomfield, 1933). Furthermore, linguists have also found it useful to refer to terms such as passive- and receptive-bilingualism to differentiate between those individuals that are unable to produce coherent utterances in a second language but who, nevertheless, are capable of displaying adequate levels of comprehension (Hockett, 1958). As Mackey (1968) has stated, however, the concept of bilingualism is entirely relative as defining competence in one language, let alone two, depends on a level of arbitrariness. Mackey (1968), therefore, defined bilingualism as the alternate use of two or more languages.

A similar view to Mackey (1968) was taken when operationalising bilingualism for the purpose of this thesis. It seemed reasonable to suggest that even under circumstances in which individuals are highly fluent in two or more languages, it is improbable that performance between the languages will be equivalent to the point were the criterion for the notion of the balanced-bilingual is met (Macnamara, 1967). If this a priori assumption is accepted, it was reasonable to argue that questions that sought to examine the factors that contribute to poorer performance in the less dominant language were more likely to succeed than attempts to establish whether a perfect balance in two languages was achievable.

One advantage of this approach to bilingual information processing was that the problematic issue of devising instruments capable of quantifying the ethereal notion of language balance was circumvented. So, an important underlying assumption of this thesis was that bilinguals are, by definition, likely to have a dominant and less dominant language. It was reasoned that the selection of individuals with clearly demarcated dominant and less dominant languages would allow a detailed and productive examination of the factors that mitigate the variation in short-term memory performance between languages.

Although research into bilingualism has received attention in the domains of linguistics (e.g., Romaine, 1989) and sociolinguistics (e.g., Edwards, 1994) the level of interest from a cognitive psychological viewpoint has been rather more constrained. In a recent volume on the theme of bilingual cognitive processing, Harris (1992) commented that the idea for the collection of papers arose from a "frustration of not easily finding published research on cognitive processing in bilinguals" (p. i). As Harris (1992) noted, while aspects of bilingualism such as second language acquisition and bilingual education had received attention, research on the cognitive functioning of such individuals had been less than systematic.

In a review of bilingual research in cognitive psychology, Keatley (1992) noted that the largest body of research was concerned with the organisation of the bilingual lexicon and the debate as to whether the bilingual's mental representations are stored in shared or separate memory systems (e.g., Kolers, 1968). A lesser area of interest assumed that the bilingual memory store is shared and, thus, addressed the question as to how the bilingual accesses the shared conceptual representations. The paradigms in which these investigations were located have followed developments in mainstream cognitive psychology. Thus, early work focused on repetition priming (e.g., Kolers, 1963), transfer of learning (e.g., Young & Saegert, 1966), and the organisation of semantic memory (e.g., Nott & Lambert, 1968). Later research focused more closely on the use of reaction time measures and investigated the cross-lingual Stroop effect (e.g., Preston & Lambert, 1969), and lexical decision tasks (e.g., Nas, 1983). It was of some interest to note that no reference was made to the study of bilingual short-term memory capacity in Keatley's (1992) review. As will become apparent, in the following sections, this is an area of research that has not been investigated systematically.

Keatley (1992) concluded that research in bilingual cognitive psychology 'has functioned as a testing ground for developed, more general models of memory or language processing' (p.40). Keatley (1992), however, was sanguine about the prospects of bilingual cognitive psychology emerging as a coherent discipline in its own right which could contribute to a general understanding of human cognition. It was important, nevertheless, to note that a recurrent danger with research in the area of bilingual information processing is that it runs the risk of falling between two theoretical stools and may, thus, fail to satisfy the interest of mainstream psychologists. The aim of this thesis was to use bilingual research, not only as a means of testing current models of processing, but to also extend and develop these theories whenever possible.

The structure of this introductory chapter is as follows. First, a brief overview of working memory theory: the paradigm in which the present thesis was located was presented. This was followed by a description of several crosslingual studies of monolingual memory performance that have supported the working memory model. Thirdly, a more exhaustive review of bilingual studies of short-term memory capacity was provided in which the divergence in findings between studies was highlighted and several important methodological and theoretical issues raised. Finally, the general research question addressed in this thesis is elaborated.

1.1: Working Memory Theory

The studies reported here were located within the general architecture of working memory theory as originally conceived by Baddeley and Hitch (1974) and modified subsequently by Baddeley (1986, 1990). This simple model captures the complexity of short-term memory phenomena and has accounted for a wide range of experimental findings. More important, the conception of short-term memory as a 'working' memory addressed the important question as to how the control processes and short-term storage mechanisms in memory are utilised by the human processing system.

During the 1960s and 1970s there was a general consensus that information in short-term memory was stored in readiness for further processing (e.g., Atkinson & Shiffrin, 1968; Craik & Lockhart, 1972, Rumelhart, Lindsay, & Norman, 1972). These models, however, made little attempt to specify precisely how information in short-term memory was utilised and what purpose was served by the temporary retention of material. This question was addressed directly by Baddeley and Hitch (1974). Unsurprisingly, they found that requiring subjects to continually rehearse an eight digit string while performing a reasoning task concurrently resulted in an increase in response latency.

What was surprising, however, was that despite a longer response latency, no corresponding increase in the proportion of errors was incurred as a function of the length of the digit string that was to be concurrently stored and rehearsed. It was, thus, possible for subjects to retain sequences of up to eight digits without incurring costs in the accuracy of a reasoning task. This finding fundamentally questioned the assumption that short-term memory consisted of a single, unitary store of 7± 2 items (Miller, 1956) or the modal model of Atkinson and Shiffrin, (1968) which predicted that the maintenance of a sequence of eight digits should cause a catastrophic impairment of processing capacity. These and other findings led Baddeley and Hitch (1974) to propose that short-term memory consisted of a number of dedicated subsystems.

The working memory architecture as currently formulated (e.g., Baddeley, 1990) is conceptualised as a tripartite system of buffers or processes that operate in combination or singly to mediate the transcoding, storage, and manipulation of information from the external physical world into the internal mental world. Currently the working memory model consists of two modality-specific slave systems. One of the slave systems is involved in the processing of verbal material (the phonological loop), another mediates the processing of visual material (the visuo-spatial scratch pad). Both slave systems are overseen by an attentional controller (the central executive).

The phonological loop component of working memory is by far the most researched and best understood process and provides a parsimonious account of a wide and complex range of phenomena. These include the phonological similarity effect (Conrad, 1964; Conrad & Hull, 1964) and the unattended speech effect (e.g., Colle & Welsh, 1976; Salamé & Baddeley, 1982). A further phenomenon that is neatly accommodated by working memory theory is the word length effect (Baddeley, Thomson & Buchanan, 1975): the inverse relationship between the spoken duration of words and memory span. In other words, the effect describes the finding that memory span for sequences of short words (e.g., cap, mat, pen) is greater than for long words (e.g., university, aluminium, tuberculosis).

The phonological loop slave system is conceptualised as consisting of two subsystems operating in tandem: a phonological store and an articulatory control process. Speech-based information is passively maintained in the phonological store subsystem where signals are subject to trace decay and become irretrievable after approximately 1.5 - 2 seconds. Information loss from the phonological store is precluded, however, by the restorative action of the articulatory control process through subvocal rehearsal. Words of short articulatory duration are rehearsed subvocally at a faster rate and occupy less temporal capacity than long words. Consequently, when information is retrieved from the phonological loop for recall, memory span for short words is greater than for long words, hence the word length effect.

A central tenet of working memory theory is that the functioning of the distinct components of working memory are capable of being fractionated through the use of secondary tasks. The procedure whereby subjects are required to engage in two or more tasks simultaneously (the dual task paradigm) remains an important feature of studies within the working memory paradigm. One of the most widely-used dual tasks is articulatory suppression where subjects engage in the concurrent articulation of an irrelevant sound or phrase, such as the, the, the (Murray, 1965). The logic of this procedure is as follows. Under articulatory suppression the renewal of traces within the phonological store is prevented as the articulatory rehearsal process is occupied by the irrelevant material. Under these circumstances, the articulatory duration of items ceases to be a determinant of a memory span that is mediated by non-phonological factors. Under articulatory suppression memory performance for verbal material is affected in predictable ways and both the phonological similarity and word length effects are eliminated (Baddeley, Lewis, & Vallar, 1984). Such findings provide further support the view that memory span for verbal material is mediated by temporal factors.

The articulatory suppression procedure is not without its critics (Parkin, 1988, 1993). It has been argued for example (Levy, 1971; Besner, Davies, & Daniels, 1981; Besner & Davelaar, 1982), that articulatory suppression disrupts the process of seriation in short-term memory rather than the process of subvocal rehearsal itself. Moreover, Levy (1981) and Margolin, Griebel and Wolford (1982) have suggested that the additional processing load demanded by concurrent articulation impairs recall ability through increased demands made on attention.

There are further details concerning the functioning of the phonological loop that remain unspecified. Longoni Richardson and Aiello (1993) and Richardson, Longini, and Di Masi (1996), for example, have questioned the notion that traces within the phonological store are irretrievable after two seconds. Their findings indicate the persistence of phonological similarity when subjects engaged in articulatory suppression for post-presentation intervals of up to 20 seconds.

Evidence from neuropsychological studies, however, go some way to counter these criticisms. A case study by Vallar and Baddeley (1984), for example, showed that patient P.V. whose memory performance did not display the characteristics of phonological loop functioning (such the word length effect) was immune to the disruptive consequences of articulatory suppression.

There are effects, however, that the relatively simple, initial account of phonological loop functioning proposed by Baddeley and Hitch (1974) cannot account for. A body of evidence has emerged, for example, that indicated that when items are matched for word length, memory span for high frequency words is greater than for low frequency words and non words (Hulme Maughan, & Brown, 1991). Moreover, a finding by Gregg, Freedman, and Smith (1989) that articulatory suppression did not eliminate frequency effects in recall tasks fundamentally questioned the assumption that memory span was exclusively mediated by word length and the rate of subvocal rehearsal. The complex matter of estimating speech rate has also been the subject of attention as Geffen and Luszcz (1983), Tehan and Humphreys (1988) and Henry and Millar (1991), for example, have suggested that variables assumed to reflect long-term memory processes also influence this variable. In addition, Monsell (1987) has questioned the use of speech rate as a measure of internal cognitive processes.

The visuo-spatial scratch pad (VSSP) may be viewed as structurally and functionally analogous to that of phonological loop. Logie (1986), for example, has shown that the presentation of irrelevant pictures interferes with the maintenance of visual information, a similar finding to that of the irrelevant speech effect (Salamé & Baddeley, 1982) for the phonological loop. Information may, thus, be fed into the VSSP either by directly through perceptual means or by the generation of imagery by the individual. Although there are similarities between these two working memory slave systems, dissociations of visual and spatial processing (e.g., Quinn & McConnell, 1994; Logie, 1986, 1989) have indicated that the architecture of this component of working memory is somewhat more complex than that of the phonological loop. That is, there is evidence that the dual visual and spatial components of the VSSP are responsible for the recognition and location of stimuli respectively (Baddeley, 1990). These additional complexities may be one important reason why progress in understanding the functioning of the VSSP has been less forthcoming (Gathercole & Baddeley, 1993).

The central executive component of the working memory troika is the least well understood and the concept has been derided as being nothing more than a conceptual rag bag or convenient homunculus (Baddeley, 1996). The most recent conceptualisation of the central executive relies heavily upon a model of attentional control developed by Norman and Shallice (1980). For the purposes of this thesis, it was sufficient to note that the putative involvement of the central executive in a wide range of short-term memory performance is disrupted by secondary tasks that require the generation of random sequences and the monitoring of output (Baddeley, 1996).

Finally, it should be noted that the notion of working memory as a general mental workspace in which information may be manipulated and processed has been applied to a wide range of psychological settings with success. Daneman and Carpenter (1980), for example, demonstrated the involvement of working memory in reading comprehension, whereas Gathercole and Baddeley (1989) have provided evidence that specific language impairment in children may be due a dysfunctional phonological loop. Other studies (e.g., Service, 1992; Service & Craik, 1993) have shown the involvement of the phonological loop in foreign language learning and second language acquisition (Ellis, 1996; Ellis & Sinclair, 1996; Papagno & Vallar, 1995). In terms of the VSSP, the suggestion has been made that this component of working memory is implicated in the retention of non verbal information (e.g., Hatano & Osawa, 1983). Taken together, then, these studies and others have indicated that the storage of information in working memory is of crucial importance in assisting a wide range of processing capabilities within the human information system.

1.2: Terminology

The variation in terminology for certain key concepts has been high across the studies discussed now and was standardised for ease of presentation. Firstly, the terms dominant and less dominant language were used in preference to mother tongue, native tongue, second, or secondary language, etc. Experience of testing bilinguals indicated that the use of the descriptor 'mother tongue', for example, is often used in a highly literal sense to denote the language of the individual's mother and not in the sense of preferred or most fluent language. The terminology favoured in this thesis, thus, diminished the possibility of confusion wherein a bilingual could plausibly be more dominant in a language other than the 'mother' tongue.

Secondly, the studies presented in this thesis (with the exception of Experiments 10 & 11) operationalised memory span as the maximum number of unrelated items that can be accurately recalled in serial order. This procedure is such that the sequence length of the items to be remembered is increased systematically until the subject is no longer able to recall the sequences correctly. Memory span is not always defined in this manner in the literature and is sometimes used to denote performance on a fixed sequence length.

Thirdly, the variation across studies in referring to different representations of number (typically from 0-9) as digits, figures, numbers, digit numbers, digit names, digit figures, number names, and so on were simplified as follows. The term digits was used when reference to stimuli under auditory presentation was made. For visual presentation the notation numerals was used to denote Arabic numerals (e.g., 1, 2, 3, etc.) and digit words to represent the written form of digits (e.g., one, two, three, etc.).

There was an equally high variation across studies when quantifying the time taken to articulate the items in question (e.g., articulation duration, spoken duration, word length, subvocal rate, rehearsal rate, and so on). This problem was further compounded for estimates of articulation time derived from speech tasks involving multiple repetitions of the items in questions. These quantifications are sometimes referred to as speech rate, when in fact they are item reading or articulation times (i.e., sec/item measures) and not rates (i.e., item/sec). The use of the terms articulation time and reading time (whether for numerals or digit words) was, therefore, preferred.

1.3: Working Memory and Cross-Lingual Memory Capacity

Miller (1956) proposed that the capacity limit of immediate memory span lies within the range of 7 ± 2 items. The Chinese, however, have been known to exceed this boundary and have recorded digit spans of 9.9 (Hoosain, 1984). It has been known for some time that the Chinese outperform English-speakers in tasks such as rote memory for text (Pyle, 1918) and memory span for digits Hao (1924). Working memory theory posits that the articulation duration of the to-be-recalled items is one crucial determinant of memory span. One explanation of the high level of performance by the Chinese in digit span tasks may be a feature of the language where digit names are monosyllabic and shorter in terms of articulation duration than, say, English even though the latter contains only one bisyllabic digit name. Several cross-linguistic studies of memory performance have tested the working memory explanation of the variation in digit span between languages.

1.3.1: Cross-Linguistic Speech Rate and Digit Span

Naveh-Benjamin and Ayres (1986) examined whether the digit span of native speakers of English, Spanish, Hebrew, and Arabic varied as a function of digit word length as estimated by syllable length and reading rate. The results indicated that digit span in English (7.21) was greater than Spanish (6.37), Hebrew (6.51) and Arabic (5.77): all the paired comparisons were reliable except between Spanish and Hebrew. Reading time in English was the shortest (256 msec/digit), followed by Spanish, then Hebrew, then Arabic (287, 309, and 370 msec/digit respectively). The paired contrasts were all reliable except that between Spanish and Hebrew. The relationship between the languages on the reading time task, thus, mirrored performance on the reading task with a larger digit span present for the language with the shortest reading time was confirmed by a reliable correlation between the variables (-0.49). Naveh-Benjamin and Ayres (1986) observed that performance on the memory span and reading tasks was related to the mean number of syllables and phonemes for digits in each language. When the portion of the variance contributed by syllable length was partialled out, the correlation between digit span and reading time was decreased to -0.24.

Naveh-Benjamin and Ayres (1986) quantified the capacity of the short-term store for each language by calculating the product of digit span and reading time. The results indicated that the memory capacity for English and Spanish (1.85 and 1.83 respectively) on the one hand and Hebrew and Arabic (2.01 and 2.13 respectively) were different, whereas the comparisons within these language pairings were not. Now, according to working memory theory, memory span is determined by the temporal capacity of the phonological loop, therefore, the measures of capacity across the languages should not vary and the values should lie between 1.5 and 2 seconds (the estimated capacity of the phonological store). The findings of Naveh-Benjamin and Ayres (1986), however, indicated the absence of a consistent relationship between memory capacity across the languages and were, thus, not in keeping with the prediction based on working memory theory. Instead, the findings indicated that performance in Hebrew and Arabic yielded higher approximations of phonological storage capacity than English and Spanish.

Naveh-Benjamin and Ayres (1986), thus, posited the existence of trade-off mechanism between syllable length and syllable articulation speed. Naveh-Benjamin and Ayres (1986) suggested that speakers of languages with a large number of syllables per word may learn to speed up the rate of production to an unspecified optimum to circumvent what they described as a universal processing-rate bottleneck as opposed to a universal store capacity (p.750).

Interesting though this suggestion was, however, a simpler explanation could account for the discrepancy in storage capacity estimates between the languages. In the Naveh-Benjamin and Ayres (1986) speeded reading task, all the subjects read the digits from left to right (Naveh-Benjamin, 1997, personal communication). It should be noted that Hebrew and Arabic text are read from left to right until a multi digit numeral appears when, curiously, the direction of reading switches. Thus, while left to right processing is the natural direction for the reading of numerals in the four languages tested by Naveh-Benjamin and Ayres (1986) it was possible that Hebrew and Arabic speakers were more familiar with reading from right to left generally. This may have resulted in a bias in which the reading of numerals from left to right may have slowed down performance, and hence a lack of comparability in the reading time measures and memory capacity between English and Spanish on the one hand, and Arabic and Hebrew on the other.

Naveh-Benjamin and Ayres (1986) made the important point that when selecting subjects for crosslingual and bilingual studies, particular attention should be paid to the language of mathematics instruction. During the piloting of their experiment, Naveh-Benjamin and Ayres (1986) observed that some subjects who reported themselves to be dominant in a mother tongue other than English had received substantive mathematics education in English in their respective native countries. Under these circumstances, performance in tasks requiring the processing of numerals by these individuals would not be comparable to that of monolingual speakers of the same language who received mathematics education in the mother tongue.

1.3.2: Developmental Cross-Lingual Differences

In a study of cross-cultural differences in cognitive processing among schoolchildren, Stevenson, Stigler, Lee, Lucker, Kitamura, Hsu (1985) noted that 70 per cent of the children in their Taiwanese sample obtained the maximum digit span allowed by their experimental procedure (i.e., 7 items). By contrast, only five per cent of the Japanese and United States children performed at ceiling. The findings from studies of cross-cultural mathematical achievement in schools (Husen, 1967; Stigler, Lee, Lucker, Stevenson, 1982) that indicated that Oriental (i.e., Chinese, Japanese, Taiwanese) children outperformed their peers in the United States and elsewhere seemed a logical basis upon to speculate that digit span performance and mathematical achievement were in some way related (this was subsequently demonstrated by Hoosain & Sallili, 1988). Stigler, Lee, and Stevenson (1986) examined the nature of the superior memory span for Chinese speakers in a series of further studies.

Stigler et al. (1986) examined auditory memory span performance for digits and words for children in first and fifth graders from Taiwan, Japan, and the U.S.A. and found that the Chinese-speaking children had a larger digit span than the American and Japanese children, whereas the Taiwanese and American children had larger word spans than the Japanese children. Stigler et al. (1986) concluded that the equivalence in word span between the Chinese and English speakers indicated that the superior Chinese digit span could not be attributed to a difference in memory capacity between these language groups. Furthermore, the similar Japanese and Chinese counting systems in (e.g., where 21 expressed verbally as two-ten-one) indicated that the larger digit span in Chinese could not be attributed to a difference between the occidental and oriental number systems.

In a second experiment, Stigler et al. (1986) contrasted performance by Chinese and English speaking children on forward and backward visual numeral span tasks.

An additional condition in which the stimuli were grouped in threes for forward recall was also included. To explain, for a 5 digit string, for example, the items were presented as two sequences of 3 + 2 numerals, for a 6 digit string presentation consisted of two sequences of 3 items, and so on. The presentation rate for both the grouped and ungrouped conditions was one item per second. This meant that for the grouped condition a sequence of three items, for example, was presented for three seconds. The reasoning behind this manipulation was that a comparison of between language performance on the grouped condition would reveal whether the Chinese children used different grouping strategies to the English-speaking children as a consequence of the different counting systems.

The results indicated that forward digit span was larger for grouped than ungrouped presentation for both the Chinese-and the English-speaking children. However, unexpectedly, no difference in forward recall was present between the languages for either the grouped or ungrouped presentation conditions: although a non significant trend toward a larger digit span in Chinese was observed. When backward recall was specified, digit span performance was impaired relative to forward recall. In this case, however, performance between the language groups was not equivalent as the decrement in performance between the directions of recall was more marked for the Chinese than the English group.

In Experiment 3, Stigler et al. (1986) measured the sound duration of Chinese and English digits and auditory digit span for groups of Chinese and English native speakers. In addition, a measure of the time taken to output the recalled sequences was taken. The results indicated a larger digit span in Chinese than English (9.2 and 7.2 respectively). The measures of sound duration indicated that Chinese digits were pronounced faster than English digits (406 and 527 msec/digit respectively). Given the shorter articulatory durations for Chinese than English, the rate of output for the digit sequences was faster in Chinese than English (approx. 220 and 540 msec/digit respectively). Moreover, when the capacity of the phonological loop for Chinese and English was estimated the average duration for maximum span length did not differ

(2423 and 2905 msec). Although this yielded numerically greater estimates of phonological loop capacity than reported by Naveh-Benjamin and Ayres (1986), it should be noted that Stigler et al. (1986) did not require speeded performance from their subjects. The difference in the estimates of phonological loop capacity between the studies was, thus, probably due to a difference in the manner in which sound durations were measured.

The findings of Stigler et al. (1986), therefore, generally supported the view that the larger memory span by speakers of Chinese was likely to be a consequence of a shorter word length for digits (see also Hoosain, 1982). Although, Stigler et al. (1986) claimed that a greater forward digit span was present for Chinese than English, this difference was, in fact, not reliable. Stigler et al. (1986) made no attempt to justify why the statistical analysis of the outcome of Experiment 2 was disregarded.

Taken together, the findings of Stevenson, et al. (1985) and Stigler et al. (1986), however, provided a neat demonstration of a developmental aspect of memory span. It will be recalled that a cross-linguistic difference between Chinese and English was present in the Stevenson, et al. (1985) study, whereas in Stigler et al.'s (1986) Experiment 2, no corresponding difference was present. A crucial difference between these studies lay in the choice of presentation modality. That is, Stevenson, et al. (1985) presented digits in the auditory modality, whereas Stigler et al.'s (1986) used visual presentation. Now, it has been suggested (Hitch & Halliday, 1983; Hitch, Halliday, Schaafstal, & Schraagen, 1988) that although children as young as 4 years show evidence of subvocal rehearsal, this is restricted to material that is presented auditorily. Children have to reach the age of about 8 years, however, before the effects of subvocal rehearsal are present for visually presented material.

If the account of the developmental differences in short-term memory processing as a function of presentation modality proposed by Hitch and co-workers is accepted, the combined results of these cross-linguistic studies supported this notion. When the opportunity for subvocal rehearsal in young children was increased under auditory presentation cross-linguistic differences in digit span were present, whereas under conditions where memory span was likely to be mediated by non-phonological processes (visual presentation) no difference between Chinese and English digit span was present.

1.3.3: Articulatory Suppression and Cross-Lingual Digit Span

The findings from the cross-linguistic studies described above suggested an inverse relationship between the articulatory duration for digits between languages and digit span. This pattern of results is neatly accommodated by working memory theory and the time-limited functioning of the phonological loop. In other words, languages with short articulation times for digits make fewer demands upon the limited temporal resources of working memory, consequently, digit span is likely to be greater compared to a language with relatively longer articulatory duration for digits. The cross-lingual variation in digit span may, thus, be viewed as an extension of the word length effect. The suggestion that variation in articulation rate accounted for the differences in cross-linguistic digit span, then, appeared a plausible explanation of this curious quirk of psycholinguistic relativity.

Chincotta and Underwood (1997) reasoned that if the larger digit span for Chinese was mediated by a relative efficiency in the articulation duration of digits, cross-linguistic differences in digit span should be abolished by concurrent articulation. If, on the other hand, the larger digit span for Chinese speakers relative to speakers of other languages persisted under articulatory suppression an alternative explanation of the Chinese superiority in digit span tasks would be required.

Chincotta and Underwood (1997) compared visual memory span for numerals by native speakers of six languages (Chinese, English, Finnish, Greek, Spanish, & Swedish) under articulatory suppression and silent recall conditions. The results indicated that the digit span of the Chinese speakers was greater than that of the remaining European languages which did not differ among themselves. Under articulatory suppression, however, no difference was present between the languages. Chincotta and Underwood (1997), thus, concluded that the superior digit span in

Chinese was determined by phonological loop functioning as articulatory suppression eliminated the advantage of this language over the remaining five.

Chincotta and Underwood (1997) found no difference in digit span among the five European languages, whereas in the Naveh-Benjamin and Ayres (1986) study, English native speakers obtained larger digit spans than their Spanish counterparts. An explanation for a lack of convergence between these studies could be that Naveh-Benjamin and Ayres (1986) excluded the number 7 (the only bisyllabic digit in English) from the set of stimuli used to measure digit span 'in order to maximise the differences between the languages' (p.743). This curious manipulation by Naveh-Benjamin and Ayres (1986) may have exaggerated the difference between English and Spanish digit span and that this plausibly explained the equivalence between these two languages in the Chincotta and Underwood (1997) study.

1.4: Working Memory and Bilingual Memory Capacity

This section presents a review of previous bilingual memory span studies that are most pertinent to the question in hand: the determinants of bilingual memory capacity. Although there was a long-established tradition in the examination of bilingual performance in the areas of number perception and subvocal counting (e.g., Dornic, 1969), the development of decoding and encoding processes (Mägiste, 1977) and the organisation of the bilingual lexicon (e.g., Kolers, 1968), this literature is simply too extensive to summarise within the constraints of this thesis. In addition, several studies (e.g., Cheung and Kemper, 1993, 1994) examined differences in memory performance between the dominant and less dominant languages of the bilingual by using fixed length serial recall tasks. It was reasoned that such approaches, while of some value in detailing aspects of bilingual memory performance such as seriation are, by definition, of lesser importance in examining the actual capacity limits bilingual memory capacity as these cannot properly be established by presenting sequences of the same length in each language.

1.4.1: The Bilingual Digit Span Effect

Hoosain (1979) postulated that for balanced bilinguals (individuals equally fluent in two languages) digit span should be equivalent regardless of the language in which recall was specified. For asymmetric bilinguals (individuals for whom one language is dominant over the other), however, Hoosain, posited that digit span would be greater in the native (or more dominant) language. Hoosain (1979) noted that forward digit span involved auditory storage, whereas backward digit span required the reordering of material and proposed that these distinct measures of memory span tapped different mental processes. Hoosain (1979), thus, suggested that these putative differences between the measures of bilingual memory capacity could be a useful tool with which to trace bilingual development. Hoosain (1979) predicted that as the level of bilingual fluency improved (i.e., from asymmetric to balanced competence) the magnitude of the difference between the languages should be reduced for both directions of recall, thus providing an index of bilingual development.

Hoosain (1979) found that forward digit span was greater in Chinese than English for both schoolchildren and undergraduates and that the magnitude of the language difference was smaller for the older age group compared to the younger one (2.6 and 2.9 digits respectively). Backward digit span, although decreased compared to forward digit span, remained greater in Chinese than English and the magnitude of the language difference was reduced correspondingly with a smaller difference for the undergraduates compared to the schoolchildren (0.6 and 0.9 digits respectively). The difference between forward and backward digit span was greater for Chinese than English, however, the magnitude of this difference between the age groups was not reliable. Hoosain's (1979) prediction that the magnitude of the difference between Chinese and English digit span would be reduced as a function of practice in the second language was, thus, not supported although the trend was in the right direction.

The findings, then, did not support the view that for individuals with a putative level of balanced bilingualism (the undergraduate group), digit span would be equivalent regardless of language. Hoosain (1979) commented that phonological differences between the Chinese and English might have had discrete effects on the auditory storage capacity required for performing memory span tasks: a suggestion that was to prove a useful explanatory principle for the effect in subsequent studies. In a further study of Chinese-English bilinguals, for example, Hoosain (1982) found that reading time for 200 numerals was correlated with auditory memory span for each language (Chinese = -0.66, English = -0.70). Moreover, Hoosain (1984) demonstrated that it is actual speech rate rather than the number of syllables that is the crucial variable in determining differences in articulation duration between languages as six takes longer to articulate than seven (see also, e.g., Baddeley, Thomson, & Buchanan, 1975).

An interesting suggestion by Hoosain (1979), was that the bilingual digit span differentials could be used to quantify bilingual fluency and to trace bilingual development. The proposed formula consisted of subtracting digit span in language one from that of language two and dividing the sum by the total memory span in both languages and multiplied by 100. According to Hoosain (1979), the quotient generated by this algorithm produced an index of balanced bilingualism when the figure was 0, first language dominance for a positive index and second language dominance for a negative index.

While this proposed index of bilingualism appeared useful, it will be noted that the positive or negative nature of the index relied crucially on how the bilinguals' languages are labelled (i.e., as language one or two). The use of this index of bilingualism was, thus, restricted to comparing groups or individuals under conditions where the decision as to which language was dominant is clear or when the groups of bilinguals under examination enjoyed the same linguistic experience with regard to the language of the home, school, and so on. More important, the index of bilingualism proposed by Hoosain (1979) would only be valid if the level of relative fluency between the languages was the only factor that mediated bilingual digit span performance. As shall be noted in due course, the evidence presented in this thesis demonstrated that this is not necessarily the case.

1.4.2: Speech Rate and Bilingual Non Word Span

The predictive power of several estimates of cognitive processing in relation to memory span for a range of stimuli (e.g., binary digits, digits, letters, and words) was investigated by Standing, Bond, Smith, and Isley (1980) to examine the extent to which each of the estimates was associated with short-term memory capacity. The findings indicated that silent and whispered reading time correlated most highly with memory span (-0.68 & -0.75 respectively). Standing et al., (1980) concluded that memory span was predicted by the rate of articulation and the number of items that could be uttered in an interval of approximately 1.8 seconds and, thus, supported the notion that memory span was determined by the temporal limitations of the phonological loop (Baddeley et al., 1975).

Standing et al. (1980) extended these findings by testing the relationship between whispered and silent reading time and auditory memory span using a sample of 14 English-French bilinguals with either English or French as the dominant language. Standing et al. (1980) quoted experimental evidence by Kassum (1967) and Pimsleur (1971) that indicated that bilingual memory span is likely to be reduced when performance is specified in the less dominant language. This suggestion generated the prediction that memory span would vary as a function of subvocalization and reading time for each language. In Experiment 3, Standing et al. (1980) presented CVC nonsense syllables spoken in either an English or French pronunciation to control for the effect of word frequency or familiarity between the languages (Watkins, 1977).

Standing et al. (1980) found an interaction between language dominance and language such that memory span was greater in the dominant language than in the less dominant language (for the English-dominant group means were English = 3.36, French = 2.97, for the French-dominant group means were French = 3.30, English = 3.11). The speech rate data were pooled by aggregating performance for the dominant language and less dominant language for both groups (homophone and heterophone conditions respectively). The results indicated that silent reading time was shorter than whispered reading time but no interaction between the factors was present.

When the time required for the subvocalization of items was calculated by multiplying the mean articulation time for the items by memory span in each language no statistical difference was present between either homophone and heterophone conditions. Despite this non reliable difference between the homophone and heterophone conditions, Standing et al. (1980) claimed, that a variation of 4 per cent (whispered reading time) and 5 per cent (silent reading time) corresponded to the difference in memory span performance between the dominant and less dominant languages. On the basis of these findings (and those of the previous two experiments) Standing et al. (1980), thus, concluded that memory span was related to rate at which material can be rehearsed subvocally. Given that Standing et al. (1980) concluded that their findings indicated a relationship between memory span and subvocal rehearsal rate, however, it was curious that no correlational statistics were reported for Experiment 3: although these were reported for Experiments 1 and 2.

The Standing et al. (1980) study was one example of the use of bilingual subjects to test predictions of information processing although it had relatively little to say about the factors that determined poorer performance in the less dominant language apart from the fact that memory span was correlated with a slower rate of articulation.

There are, however, a number of problems associated with this study that call into question even the modest conclusion arrived at. Firstly, although the use of non words was an ingenious way of equating the imbalance between the strength of long-term memory representations between the languages, there was no indication as to whether the items were pronounced as intended during the reading tasks: in the case of silent reading, particularly, this would appear to be a major shortcoming. It was, thus, possible that the reading time measures (silent or whispered) did not correspond to the utterances in the memory span task. Support for this notion may be found by comparing performance between the whispered and silent reading tasks. For the French dominant group, for example, the difference between French and English silent reading time was 6.29 seconds, whereas for the whispered reading task the difference was 0.35 seconds. It would, thus, appear that the reading time estimates lacked comparability.

A further objection to the findings of this study lay in the manner in which the memory span and reading time data were analysed. The memory span data, for example were analysed by a two-way analysis of variance in which test language and mother tongue were the factors. Although it was reported that this analysis revealed a significant interaction between the factors such that memory span was greater in the mother tongue, this was not examined in closer detail. It could not, therefore, be established what the precise nature of the interaction was. Inspection of the means indicated that the language difference for the English-dominant group was greater (0.39) than for the French dominant group (0.19). Thus, it was possible that the source of the interaction lay solely in the performance by the English dominant group.

In the analysis of the reading time task, on the other hand, one factor consisted of homophone and heterophone conditions in which the data was pooled across the bilingual groups and the remaining factor consisted of whispered and silent reading conditions. This design, therefore, did not allow a detailed examination of how performance varied as a function of language dominance.

A final criticism of the study of bilinguals by Standing et al. (1980) lay in a lack of correspondence between the manner in which speech rate and memory span measures were quantified. Note that reading time was estimated using printed representations of non words, whereas memory span was measured in the auditory modality. Without pre-empting the conclusions expounded in this thesis, it will become clear that a lack of consistency in presentation modality within studies was identified as a major source of error in studies of bilingual memory span.

1.4.3: A Bilingual Word Length Effect

Ellis and Hennelly (1980) observed that Welsh digits took longer to pronounce than English digits (despite an approximately equal number of syllables between the languages). In order to test this notion empirically, estimates of the articulation duration (word length) for digits in each language were obtained by requiring bilingual subjects to read aloud a list of 200 numerals. The criterion for establishing an adequate level of bilingualism was that the subjects should have been educated in both Welsh and English. In addition, the subjects self-rated language dominance on a scale of 1-10.

The results, indicated a shorter numeral reading time for English than Welsh (321 and 385 msec/digit respectively). Moreover, every subject read numerals faster in English than Welsh regardless of self-rated competence. Ellis and Hennelly (1980) thus, concluded that six English digits could be articulated in the time taken to articulate 5 Welsh digits.

On the basis of working memory theory, these findings generated the prediction that the shorter word length in English than Welsh would occasion a corresponding larger digit span in English than Welsh. This prediction was tested in Experiment 2 in which Welsh and English auditory memory spans was measured for the same subjects. An additional two conditions involved the translation of items from the language of presentation prior to recall (e.g., when Welsh digits were presented recall was specified in English and vice versa). The results indicated that English digit span was greater than Welsh digit span (6.55 and 5.77 respectively). Ellis and Hennelly (1980), thus, attributed the superior memory span in English to a shorter reading time for English digits relative to Welsh digits.

Before concluding that reading time was a causal determinant of memory span, Ellis and Hennelly (1980) discussed the possibility that the findings of Experiments 1 and 2 may have been due to a differential level of familiarity for Welsh and English digits. That is, it may have been the case that the Welsh dominant speakers in the sample may have been more practised in the use of English digits relative to Welsh.

This possibility was tested in a further series of studies that constituted Experiment 3. Here, a different sample of 8 Welsh-English bilinguals was selected and numeral reading time (Experiment 3a) and digit word reading time measured (Experiment 3b). The findings indicated that numeral reading time was shorter for English than Welsh (288 and 333 msec/digit respectively) and, thus, replicated the findings of Experiment 1. The results of the digit word reading task, by contrast, indicated that no difference was present in reading time between English and Welsh (308 and 293 msec/digit respectively).

Ellis and Hennelly (1980) explained the discrepancy between numeral and digit word reading time as a consequence of higher familiarity in Welsh than English. That is, they reasoned that the equivalence in digit word reading time between the languages was occasioned by a higher level of fluency in Welsh (as evidenced self-ratings) which, in turn, allowed a putative word length advantage for digit names in English (as evidenced by the findings of Experiments 1 and 3a) to be attenuated to the point of equivalence.

Ellis and Hennelly (1980) reasoned that if the difference in auditory digit span between Welsh and English was mediated by variation in the word length for digits between the languages, articulatory suppression should eliminate, or at least reduce the bilingual digit span effect observed in Experiment 1. In Experiment 3c, therefore, digit word memory span measures were taken for the same sample under conditions where subvocal rehearsal was prevented by requiring subject to whisper the sequence a-b-c-d continuously during presentation.

The results indicated that suppressed digit word span in Welsh and English were equivalent (3.75 and 4 respectively). Ellis and Hennelly (1980), then argued that the outcome of the digit word span task should be compared to those of Experiment 2 where for auditory presentation a larger digit span was obtained for English than Welsh. Ellis and Hennelly (1980) concluded that "the bilingual digit span differential is a word-length effect" (p.49) and provided support for working memory theory and the suggestion that memory span was principally mediated by the articulatory duration of the to be remembered items and the rate of subvocal rehearsal.

Finally, Ellis and Hennelly (1980) compared Welsh and USA norms for the digit span subtest of the Wechsler Intelligence Scale Children (WISC, Wechsler, 1949) and found that the Welsh norms for forward and backward recall were consistently lower than the USA ones. Ellis and Hennelly (1980) put forward the view that this pattern of performance reflected a putative longer word length for Welsh digits rather than a lower intellectual ability for Welsh children in relation to their counterparts in the USA.

1.4.4: Mother Tongue Superiority

Da Costa Pinto (1991) noted the suggestion by Ellis and Hennelly (1980) that the under-performance of Welsh children in relation to peers in the U.S.A. on the digit span subtest of the WISC could be a direct consequence of differences in word length between the languages. An examination of WISC digit span norms across seven languages revealed that performance by Portuguese and Brazilian children was poorer relative to the remaining language groups (e.g., German, Italian, etc.). Da Costa Pinto (1991), therefore, suggested that variation in performance across languages may have been a consequence of a longer word length for digits in Portuguese which contains eight bisyllabic words relative to, say, German which contains only one bisyllabic digit word.

This explanation, however, did not account for performance in Italian, a language that contains eight bisyllabic digit words and for which digit span should, theoretically, be poorer compared to Portuguese. Moreover, the digit span norms for Italian were equivalent to those for English (with two bisyllabic digit words) and marginally superior to German. A plausible alternative explanation was that the WISC digit span norms in da Costa Pinto's (1991) comparison were established over a range of 33 years (i.e., from 1949, in the case of the USA norms to 1982 in the case of Spanish). As Aiken (1991) has noted, rapid social and educational change quickly outdate norms, therefore, the cross-linguistic comparison of performance over this length of time was likely to have inaccurate.

Da Costa Pinto (1991) measured reading time for 50 numerals in both random and sequential order (i.e., 0, 1, 2, ... 9) for 5 bilingual pairings (English being the second language for all groups). In addition, monolingual English performance was also measured and served as a control. The results indicated that when performance was specified in the dominant language, reading time for the random sequence was equivalent across all six groups. Reading time for the sequential order of presentation was shorter for French than Italian and no other differences between the languages were present: although the trends were broadly consistent with the variation in articulatory duration across the languages as estimated by syllable length. That is, when the data were pooled according to languages with a similar number of bisyllabic digit words, sequential numeral reading time was shorter for English and German than Spanish and Italian (means = 7.7 and 9.8 seconds respectively). This suggested that the absence of reliable differences across the languages may have been due to a lack of statistical power in the design.

Nevertheless, the variation in performance across the individual groups was minimal and, therefore, not as dramatic as predicted by the view that word length was of major consequence in mediating performance in numeral reading time as suggested by Ellis and Hennelly (1980) and Naveh-Benjamin and Ayres (1986). On the basis of these findings, then, da Costa Pinto (1991) concluded that the deleterious consequence of digit word length on digit span may have been exaggerated. Unfortunately, this prediction was not tested as da Costa Pinto (1991) was unable to measure the digit span of these individuals.

In a second experiment , da Costa Pinto (1991), examined the implications of the Ellis and Hennelly (1980) study more closely. The motivation for this was that although previous studies had clearly indicated the existence of bilingual digit span effect, the Hoosain (1979) and Zhang and Simon (1985) studies had tested a language pairing (Chinese-English) in which a putative higher of familiarity and shorter word length were confounded. Da Costa Pinto (1991) reasoned that testing a language pairing in which the discrepancy in word length and familiarity between the languages varied in the opposite direction (i.e., Portuguese and English) would allow a more informative replication of Ellis and Hennelly (1980) than the Chinese-English studies (Hoosain, 1979; Zhang & Simon, 1985).

The results indicated that Portuguese dominant-Portuguese-English bilinguals had a shorter reading time in the dominant than the less dominant language for both numeral (means = 57.2 and 81.4 seconds respectively) and digit word (means = 58.0 and 65.4 seconds respectively) representations of digits. Interestingly, no difference between the representations of number was present in the dominant language. The results of the memory span task indicated that auditory digit span was greater in Portuguese than English (means = 7.00 and 6.00 respectively). Furthermore, under articulatory suppression, although performance was reduced overall, the relationship between the languages for digit word span remained intact (means = 4.3 and 3.6 respectively). Thus, in Experiment 2, articulatory suppression did not abolish the language differential between Portuguese and English present in the silent recall condition.

Da Costa Pinto (1991) concluded that although the relationship between reading rate and memory span was supported, in this case a shorter reading time and larger memory span for Portuguese in relation to English occurred despite a longer digit word length measured in syllables and phonemes for the former. This finding supported Baddeley et al.'s (1975) view that articulation time rather than syllable length was the crucial factor that mediated memory span performance. The finding that a superior auditory digit span in Portuguese under silent recall persisted under articulatory suppression contradicted those of Ellis and Hennelly (1980). Da Costa Pinto (1991), thus, concluded that bilingual memory span was determined by a higher level of familiarity with digits in the dominant language. Moreover, da Costa Pinto (1991) suggested that the findings of Ellis and Hennelly (1980) may have been artifactual and a case of specific bilingualism as Welsh speakers display a preference for English digits even when speaking in the dominant language. Based on these findings, then, da Costa Pinto (1991) asserted that bilinguals are likely to obtain larger memory spans in the dominant language: the so-called mother tongue superiority effect.

Of course, strictly speaking the results of da Costa Pinto's (1991) Experiment 2, did not contradict the Ellis and Hennelly (1980) position. It should be noted that the pattern of findings for reading tasks in the da Costa Pinto (1991) study did not follow the same pattern as those in the Ellis and Hennelly (1980) study. In the former study, both digit word and numeral reading times were shorter in Portuguese than English, whereas in the latter study a shorter reading time for English was found for numerals and no difference was present for digit words. This left da Costa Pinto's (1991) conclusions open to the criticism that the level of English proficiency of his subjects was less than fluent (Chincotta & Hoosain, 1995).

In order to disprove the view propounded by Ellis and Hennelly (1980) that word length was a critical mediator of the bilingual memory span effect, the comparable and crucial test required a bilingual sample for which reading time in the less-dominant language was shorter than that in the dominant language. Only then, could the word length and mother tongue superiority hypotheses be pitted against each other. Thus, instead of predicting that digit span would always be superior in the mother tongue (or the dominant language) a more logical conclusion was that the relationship between the languages in bilingual reading time and memory span for digits was likely to vary as a function of level of relative fluency between the languages.

1.4.5: Long-Term Memory and Bilingual Digit Span

Hulme, Maughan, and Brown (1991) found that memory span was greater for words than non words even when the articulation duration of both sets of items was matched. Under these conditions the difference in memory span could not be attributed to a variation in the rate of subvocal rehearsal, therefore Hulme et al. (1991) concluded that the superior memory span for words in relation to non word was mediated by a contribution from long-term memory for the former.

Brown and Hulme (1992) tested this notion further by examining bilingual digit span in a group of English schoolchildren that were in the relatively early stages of learning French. Brown and Hulme (1992) reasoned that if the quality of long-term memory representations made a contribution to memory span that was independent of articulation time memory span for French digits would be greater for these subjects even in a condition in which subvocal rehearsal was prevented.

Although the published procedure for this experiment was incomplete, a personal communication by Brown (1997) clarified the situation. For the estimation of speech rate, the subjects were required to articulate a sequence consisting of the digits 1-5 in each language (i.e., one, two, three, four, five, one, two, three, etc.) in each language for 20 seconds. The mean speech rate for each language was calculated on the basis of the number of articulations during this interval.

The results of the articulation time task indicated that speech rate was faster in English than French (means = 4.5 and 3.4 items/sec respectively). Correspondingly, the results of the digit word span under the silent recall condition indicated a larger memory span for English than French (means = 6.1 and 4.8 respectively). Although digit word span under articulatory suppression was reliably reduced, the relationship between English and French was preserved (means = 3.6 and 2.9 respectively). These findings suggested that explanations of the bilingual digit span effect based on word length differences between languages and a consequent variation in the rate of subvocal rehearsal did not account for the persistence of a superior digit span in the dominant language under concurrent articulation.

The findings of Brown and Hulme (1992), thus, replicated those of da Costa Pinto (1991) in that a superior digit span was obtained in the dominant language under both silent and suppressed recall. The convergence between these studies, however, could be interpreted in two opposing ways. On the one hand, the it could be argued that together Brown and Hulme (1992) and da Costa Pinto (1991) provided a refutation of the conclusion by Ellis and Hennelly (1980) that the bilingual digit span effect was mediated by word length. On the other hand, if it is recalled that the subjects tested by Brown and Hulme (1992) were second language learners of French, the convergence between these studies is, arguably, further evidence with which to question the level of competence in English of da Costa Pinto's (1991) subjects (Chincotta & Hoosain, 1995).

One problem with the Brown and Hulme (1992) study was that although the stimuli in the memory span task were presented as digit words, written responses were in the form of numerals. This procedure may have unduly favoured performance in the dominant language as the transcoding from a digit word stimulus to a numeral in English was likely to be easier than in French (Ellis, 1992). This is not to say that performance in the Brown and Hulme (1992) study was solely mediated by this transcoding factor, given the imbalance in fluency between the languages it was not surprising that these subjects obtained a larger digit span in English. Moreover, articulatory suppression was required throughout both the presentation and recall phases of the trials: a departure from the procedure described by Ellis and Hennelly (1980) and da Costa Pinto (1991).

1.4.6: Articulation Time and Bilingual Digit Span

The relationship between articulation time and auditory digit span for children and adults was examined by Elliot (1992) using four distinct bilingual pairings in Singapore. In this multilingual society the official language of schooling is English. For those individuals for whom English is the language of the home, however, Mandarin is taught as a second language, whereas individuals from Mandarin-, Hokkien- and Malay (Bhasa)-speaking homes, receive additional instruction in either Mandarin (in the first two cases) or Malaysian. It was, thus, possible to obtain measures of performance in English across all the groups.

An interesting feature of this study was that for two bilingual pairings (Malay-English and English-Mandarin) the syllable length of digits was shorter in the second language than the mother tongue. Malay contains eight bisyllabic and one trisyllabic digit names, in Mandarin and Hokkien digits are all monosyllabic, whereas the English equivalents contain eight monosyllabic and one bisyllabic items (means = 2.11, 1 and 1.11 syllables per digit respectively). Elliot (1992) was, thus, in a position to clarify whether it was possible for bilinguals to obtain shorter articulation times and longer memory spans in a language other than the language of the home, as in the case of Ellis and Hennelly (1980) or whether performance would be superior in the mother tongue as suggested by da Costa Pinto (1991).

The findings indicated that English auditory span did not vary across the bilingual pairings, however, variation was present across the remaining languages. Here, digit span for Malay was lower than Chinese performance by 'native' speakers, however, despite a difference of a difference of 1 syllable per digit, Malay span was not significantly shorter compared to English when performance was by the 'native' speakers. The within-group results indicated that both age groups of the Malay-English bilinguals a larger digit span obtained a larger digit span in English than Malay. Similarly, both age groups of the Mandarin-English bilingual type had a larger span in Mandarin. The results for the Hokkien-English group varied between age groups: the children had larger spans in Hokkien, whereas the adults showed no difference between the languages. Finally, both age groups of the English-Mandarin pairing obtained equivalent digit spans between the languages. These findings were, thus, broadly, if not wholly, consistent with the view that bilingual memory span tends to be poorer in the language with longer spoken durations as estimated by syllable count. However, before any conclusions could be made, it was necessary to establish the variation in actual spoken duration between the languages (Hoosain, 1982, 1984).

Articulation rate measures were obtained by requiring subjects to memorise a string of 5 (in case of children) and 9 digits (in the case of adults) and to repeat the sequence aloud 5 times (Elliot, 1995, personal communication). The results indicated that articulation rate for English did not vary across the bilingual groups. Differences in articulation rate, however, were present between the languages. Here, articulation rate was slower for Malay compared to the two Chinese dialects except for performance in Mandarin by the English mother tongue individuals which, in turn, was slower relative to the Mandarin mother tongue individuals. The within-group comparisons indicated that the Malay-English individuals had a faster articulation rate in English than Malay, and both the Mandarin-English and English-Mandarin groups articulated digits faster in Mandarin than English: these relationships held for both children and adults.

Performance for the Hokkien-English group varied between the age groups: the children showed no difference between the languages, whereas the adults articulated faster in Hokkien.

Elliot (1992) reported correlational associations between articulation time and digit span for both English and for the remaining languages when the data were pooled: a pattern consistent across the age groups. However, these global correlations disguised the nature of the associations between the variables for the individual bilingual pairings. Note, for example, that despite a faster articulation rate in Mandarin than English for members of the English-Mandarin bilingual pairing, no difference in memory span between these languages was present. Similarly, the children in the Hokkien-English group obtained equivalent articulation rates between the languages and yet obtained a larger memory span in Hokkien than English. Moreover, it was curious that despite a difference of 1 syllable/digit between Malay and English performance between these languages across the bilingual groups (i.e., for native speaker measures in either language) did not differ neither in terms of articulation rate nor memory span.

One possible confounding factor in the Elliot (1992) study was that all his subjects (with the exception of the Mandarin-English adult group) received their schooling in English. This could account for the absence of variation across the bilingual pairings for both the articulation and memory span tasks when performance was specified in English. This was some indication, then, that the language of schooling was an important determinant of bilingual digit span. Variation in performance between the mother tongue languages of the respective groups, when present, occurred between Malay and the Chinese dialects. Here the pattern of findings was consistent with the view that memory span tended toward being greater in the language with faster articulation rates for digits.

Taken together, the findings of Elliot (1992), were mixed in the sense that while some support for the notion that articulation rate was an important factor in mediating the bilingual digit span effect, it was equally clear that an explanation of the phenomenon based on these factors alone did not account for the full range of performance across the individual bilingual pairings. As Elliot (1992) himself noted, it seemed likely that familiarity affected both articulation and memory span performance and, therefore, it could not be assumed that the effect was mediated by linguistic factors alone.

1.4.7: Articulatory Suppression and Bilingual Digit Span

Chincotta and Hoosain (1995) argued that the convergence between the findings of da Costa Pinto (1991) and Brown and Hulme (1992), suggested that the circumstance wherein articulatory suppression did not eliminate the language differential in bilingual digit span tasks arose when a relatively low level of bilingual fluency was present. Chincotta and Hoosain (1995), thus, contrasted the effect of articulatory suppression on bilingual digit span for a group of self-rated balanced English-Spanish and asymmetric Chinese (Cantonese)-English bilinguals. It was reasoned that if da Costa Pinto's (1991) view that digit span was mediated by a greater familiarity in the mother tongue, the hypothesised differentials under silent recall conditions should persist under articulatory suppression for both bilingual types. On the other hand, should articulatory suppression eliminate the bilingual digit span effect for both bilingual pairings this would support Ellis and Hennelly's (1980) view that bilingual digit span effects are determined by a variation in word length and the rate of subvocal rehearsal. A potential third outcome wherein articulatory suppression eliminated the difference in digit span for the balanced bilinguals and not for the asymmetric bilinguals would provide partial support for Hoosain's (1979) view that the magnitude of the bilingual digit span effect would decrease as a function of fluency.

Chincotta and Hoosain (1995) measured reading time by requiring English-Spanish bilinguals to read 200 numerals: digit span measures were taken in both the auditory and visual modalities. The results of the reading task indicated that reading time was shorter in English than Spanish (330 and 439 msec/digit respectively): all but one of the 26 subjects read digits faster in English. The results of the memory span tasks indicated a larger digit span in English than Spanish in the auditory (6.85 and 5.54 respectively) and visual (6.46 and 5.96 respectively) modalities under silent recall. The digit span differential between the languages in both modalities, however, was eliminated under articulatory suppression.

On the basis of self-rated language dominance, Chincotta and Hoosain (1995) divided the sample into Spanish and English dominant groups and re-analysed the memory span data accordingly. The findings indicated that the Spanish-dominant group had a larger digit span in English than Spanish (auditory = 6.29 and 5.29, visual = 6.43 and 5.43 respectively): once again articulatory suppression eliminated the language difference. The results for the English-dominant group were identical except that the difference in visual digit span under silent recall was not reliable.

These findings, thus, replicated those of Ellis and Hennelly (1980) in that a group of bilinguals obtained a larger digit span and shorter reading time in a language in which self-rated competence was lower. Moreover, the finding that articulatory suppression eliminated the bilingual digit span difference supported the view that the superior performance in English was mediated by a word length advantage for digits in the same language over Spanish.

Experiment 2, replicated Experiment 1 for Chinese-English bilinguals (except that only visual digit span measures were taken). In this case, however, the mother tongue (da Costa Pinto, 1991) and the word length (Ellis & Hennelly, 1980) hypotheses predicted an identical outcome for silent recall as Chinese was both the word length advantaged language (Hoosain, 1984) and the dominant language according to self-ratings. Each hypothesis, however, predicted a different outcome in terms of the effect of articulatory suppression. According to Ellis and Hennelly (1980) digit span differences should be eliminated under this procedure, whereas da Costa Pinto (1991) predicted that the digit span advantage should persist even under suppression.

The results indicated that numeral reading time was faster in Chinese than English (265 and 395 msec/digit respectively) and performance on the digit span task followed the same pattern (8.03 and 6.59 respectively): a difference that was eliminated under articulatory suppression (4.84 and 4.94 respectively).

Taken together, the results of Experiments 1 and 2 indicated that articulatory suppression consistently abolished the bilingual digit span differentials for both the balanced and asymmetric bilingual types. These findings suggested one explanation for the persistence of a bilingual digit span effect in da Costa Pinto's (1991) study was a relatively low level of fluency in English: a notion reinforced by the identical outcome between this study and that of Brown and Hulme (1992) with regard to the effect of articulatory suppression on bilingual digit span.

1.5: The Research Question

It was clear from the above literature review that studies of cross-lingual human information processing (Naveh-Benjamin & Ayres, 1986; Chincotta & Underwood, 1997) have proved useful in testing predictions based on working memory theory. These studies demonstrated that the variation in digit span across languages may be explained by differences in the word length of digits and the limited temporal capacity of the phonological loop. It was equally clear, however, that attempts to explain the bilingual digit span effect in corresponding terms have resulted in a lack of convergence across studies.

On the one hand, Ellis and Hennelly (1980) and Chincotta and Hoosain (1995) claimed that the bilingual digit span effect was mediated by processes akin to those that determine cross-lingual variation in performance. On the other hand, da Costa Pinto (1991) and Brown and Hulme (1992), Elliot (1992), have argued that explanations of the bilingual digit span effect based on word length and the rate of subvocal rehearsal alone do not provide an adequate account of the range of findings. These latter authors have, thus, proposed that greater attention to should be paid to factors related to familiarity and fluency to explain the variation in performance between the dominant and less dominant languages more fully. A reasonable summary of the findings of bilingual digit span studies would describe these as useful, in that the effect was recorded, but limited in that the factors that mediate the variation in digit span performance between the bilingual's languages remained unspecified.

Attempts to specify the determinants of bilingual memory capacity appear to have been abandoned in recent years. One explanation for the dearth of a continued and systematic examination of bilingual memory capacity since Ellis and Hennelly (1980) was that this study provided, what appeared to be incontrovertible, support for the view that bilingual memory span was mediated by subvocal rehearsal. The demonstration that a longer spoken duration for Welsh digits accounted for the superior performance in the less dominant language of Welsh-English bilinguals was powerful support for the view that memory capacity was determined by the word length. Having established this finding, it was difficult to see what benefits further research in this specific area might have: Ellis (1992), however, pursued the notion that Welsh speakers were disadvantaged relative to English speakers in arithmetic with some success.

Although the findings of da Costa Pinto (1991) and Brown and Hulme (1992) contradicted those of Ellis and Hennelly (1980), the divergence between the findings has been explained in terms of an overestimation of bilingual fluency in the studies that have failed to replicate effects of articulatory suppression on the bilingual digit span effect. Nevertheless, as Ellis and Hennelly (1980) themselves have posited, it was possible that a preference for Welsh speakers to use English digits even when speaking in the dominant language suggested that their findings were an illustration of a specific case of bilingualism. In this case, any attempts to disprove the conclusions of Ellis and Hennelly (1980) may be countered quite simply on the grounds that their findings were not generalizable to other bilingual pairings.

A recent search using the Bath Information and Data Services (BIDS), not an exhaustive database by any account, revealed that the Ellis and Hennelly (1980) study was cited in 70 research articles since publication: a not inconsiderable number. When the additional frequency of citations in texts other than research papers is taken into account, this paper is, by far, the most widely cited, and best-known of the bilingual memory span studies to date. The findings of Ellis and Hennelly (1980) are, thus, frequently cited as evidence that subvocal rehearsal mediates bilingual memory span and a neat demonstration of the efficacy of articulatory suppression in eliminating the effect of word length on memory span (e.g., Baddeley, 1990). This has resulted in the findings of Ellis and Hennelly (1980) being entrenched in the working memory literature where they are reinforced by continuous citation. It seemed reasonable to suggest that an over-reliance on the results of Ellis and Hennelly (1980) has, unfortunately, resulted in scant attention being paid to alternative interpretations of the bilingual digit span effect. For the reasons outlined above, it has proved particularly difficult to dislodge Ellis and Hennelly (1980) from the pantheon of studies that support a relatively simple version of working memory theory.

The substantial evidence questioning some fundamental assumptions of working memory theory (e.g., Hulme et al., 1991; Cowan et al., 1992) has resulted in a reconceptualisation and reformulation of both the phonological loop (Gathercole & Baddeley, 1993; Gathercole & Martin, 1996) and visuo-spatial sketchpad (Logie, 1995) components of the model. As understanding of the determinants of monolingual memory capacity has developed, modifications to working memory theory have been made accordingly. There exists, therefore, a commensurate need to update the interpretation of the bilingual digit span effect.

Chapter 2

Mother Tongue, Language of Schooling and Bilingual Digit Span

It has been well established that digit span varies considerably across languages ranging from a high of 9.9 for Chinese (Hoosain, 1984) to a low of 5.7 for Arabic (Naveh-Benjamin & Ayres, 1986; see also, e.g., Stigler, Lee, & Stevenson, 1986). This range of findings may be neatly accommodated by the phonological loop component of Baddeley's working memory model (e.g., 1990) which proposes that individual differences in both overt speech rate and phonological loop capacity determine memory span. The view that variation in digit span performance across languages is related to phonological loop functioning was supported by a study by Chincotta and Underwood (1997) that demonstrated that a superior digit span for the Chinese over speakers of five European languages was eliminated under articulatory suppression.

The cross-linguistic variation in digit span present in monolinguals is also observed between the languages of the bilingual (e.g., Ellis & Hennelly, 1980; da Costa Pinto, 1991; Elliot, 1992; Chincotta & Hoosain, 1995). As has been noted, within the working memory paradigm cross-linguistic variation in digit span may be explained as arising from differences in articulation time for digits between languages. The extent to which working memory theory can similarly account for the range of findings of bilingual span performance, however, is unclear.

2.1: Working Memory Theory and Bilingual Digit Span

Ellis and Hennelly (1980) observed that Welsh digits took longer to articulate than English digits and used reading time for a sequence of 200 random Arabic numerals as a measure of word length differences between these languages. A faster reading time in English was taken as indication of a word length advantage over Welsh. Despite a majority of subjects having rated themselves more proficient in Welsh, a faster reading time for English numerals reliably predicted larger digit spans for auditorily presented digits in English compared to Welsh. Moreover, when memory span for digit words was measured under conditions of articulatory suppression, differences in digit span between languages were eliminated. Ellis and Hennelly (1980) concluded that digit span differences between Welsh and English were an effect of word length and supported the view that surface features of a language have a powerful impact upon working memory capacity, one capable of overriding differences in relative proficiency between the languages of the bilingual.

Da Costa Pinto (1991) examined the effect of word length on digit span for Portuguese-English bilinguals, and used syllable- and phoneme-count as metrics of articulation time between the languages. A relationship between digit reading rate and digit span was confirmed, with faster articulation and higher digit span in Portuguese even though Portuguese digit names contain more syllables and phonemes than their English equivalents. This finding indicated that speaker-independent measures of word length (such as syllable and phonemes) are problematic in explaining differential digit spans in bilinguals. Although the relationship between reading rate and digit span was in keeping with predictions based on working memory theory, a finding that larger digit span performance in Portuguese was maintained with the introduction of an articulatory suppression task was not.

This finding led da Costa Pinto (1991) to claim that articulation rate did not account for all the variance observed for digit span differences between languages. Da Costa Pinto (1991) suggested that a familiarity effect arising from massive practice for digits in the mother tongue may have been partly responsible for the continued digit span superiority of Portuguese over English even under conditions of articulatory suppression. Da Costa Pinto (1991), thus, posited that speech rate will be faster and digit span greater in the first language of the bilingual -- the so-called superiority of the mother tongue.

Da Costa Pinto (1991) claimed the effects of word length on bilingual digit span reported by Ellis and Hennelly (1980) may have been exaggerated. There may be some substance to this suggestion given the indirectness of the self rating measures used by Ellis and Hennelly (1980) to establish the language proficiency of subjects. It is not inconceivable, that Welsh-English bilinguals were more dominant in English, at least for digits. Ellis and Hennelly referred to such a possibility when a preference by Welsh speakers for English digit names whilst speaking in Welsh was noted. This feature of Welsh-English bilingualism may have favoured digit reading and recall in English over Welsh unduly.

However, the da Costa Pinto (1991) explanation of the Ellis and Hennelly (1980) results was weakened by the results of a study by Chincotta and Hoosain (1995). They found that Spanish-English bilinguals with a higher self-rated proficiency in Spanish obtained faster digit reading rates and larger digit spans in English. In addition, Chincotta and Hoosain (1995) demonstrated that articulatory suppression consistently eliminated the between-language difference in digit span for both balanced and asymmetric bilinguals. Although the persistence of bilingual digit span differences under conditions of articulatory suppression, had been reported by Brown and Hulme (1992), this was observed among English school children 'in the relatively early stages of learning French' (p.115). Chincotta and Hoosain (1995), thus, argued that this was some indication that the level of bilingualism of da Costa Pinto's subjects may have been overestimated.

The interpretation and understanding of bilingual digit span performance have proved substantially more complex than that of monolingual cross-linguistic differences. It is significant, nevertheless, that in the cited studies, digit span performance is related to the speed of articulation for digits rather than speaker-independent measures of word length such as syllable, These results that are in keeping with working memory theory. It seemed evident that an examination of the bilingual digit span effect would be more productive if greater consideration was given to factors exerting an influence upon individual differences in language proficiency in the respective languages of the bilingual. The crucial variables affecting bilingual digit span were, thus, likely to lie in factors that influence actual speech rate for digits in either language.

Evidence from developmental studies of monolingual memory span (Hulme, Thomson, Muir & Lawrence, 1984; Hulme & Muir, 1985) has demonstrated that short-term memory capacity remains constant after early childhood (4 years) and that the increases in memory span observed during maturation are likely to arise from corresponding increases in speech rate. Although, the precise nature of processes underlying faster articulation remains unspecified, it seems probable that this results from improvements in speech motor skills (Hulme et al., 1984). Henry and Millar (1993) proposed a model where three factors were considered to have an effect upon increases in memory span; faster speed of retrieval from phonological memory; greater experience in using the speech output system, and increased facility to utilise long-term lexical memory. It seemed reasonable to suggest that similar factors impinge upon the second language functioning of the bilingual.

Hulme, Maughan, and Brown (1991) investigated the contribution of long-term memory to short-term memory span. Here, memory span was found to be greater for words than nonwords when both sets of items were matched for articulation duration. Under these conditions, differences in span could not be attributed to differences in the rate of articulation. Instead, larger memory span for words was probably due to a distinct contribution from long-term memory as nonword stimuli were unlikely to have long-term memory representations. In a further demonstration of a long-term memory contribution to memory span, Hulme et al. (1991) presented Italian words to English native speakers with no knowledge of Italian. Teaching subjects the English translations for Italian words increased memory span for them. Although an increase in memory span for Italian was accompanied by a corresponding increase in speech rate after the learning of English equivalents, memory span was shorter than would have been predicted by articulation rate. The observed increase in memory span was interpreted as an effect arising from the creation of long-term memory representations for Italian words arising from a relatively brief period of training.

The contribution to memory span accruing from exposure to a foreign language over much longer periods may be evaluated in a study of second language acquisition by Mägiste (1979). Developmental changes in a variety of linguistic information processing tasks were traced for a group of German mother tongue speakers attending a private German school in Stockholm. German was the language associated with faster reaction times for all tasks for subjects with approximately 5.5 year's residence in Sweden. After this length of residence, the point of language balance and point of shift toward better performance in Swedish occurred, more or less, simultaneously. Thereafter, performance in Swedish compared to German stabilised and continued to be favoured for the former.

The evidence presented thus far strongly suggested that speech rate (through faster retrieval from phonological memory and more efficient use of speech output systems) and familiarity effects (through long-term lexical memory influences on short-term memory) are influential factors in mediating language proficiency among bilinguals. In addition, the findings of cross-linguistic studies demonstrated that the effects of speech rate and differences in the articulatory complexity of digit names between languages are not mutually exclusive. It was reasoned that a more productive examination of bilingual memory span performance necessitated greater attention to the actual factors that influence speech rate and familiarity.

2.2: A Test of Three Hypotheses

Naveh-Benjamin and Ayres (1986), put forward the view that, for bilinguals, the language in which mathematical and science training is received may be favoured in digit span tasks. In circumstances where mother tongue and language of schooling are different, it was reasonable to suggest that the enormous discrepancy between the languages in the level of practice in counting and computation, associated especially with elementary education, is capable of engendering a higher level of familiarity and competence with digits in the language of instruction than in the mother tongue. Massive practice relating to digits could plausibly facilitate faster reading rates and larger digit spans, and override individual differences in number names between the dominant and less dominant languages.

This possibility had not been tested empirically, neither had the bilingual digit span studies reported to date controlled for the effects of different linguistic experiences in respect of schooling and mother tongue (or language of the home). For example, in the Ellis and Hennelly (1980) study, subjects were considered bilingual if they received education in both Welsh and English. The larger digit span for English observed in Welsh mother tongue speakers may have resulted from the effect of either schooling or mother tongue factors or may be an artifact arising from a particular combination of bilingual backgrounds in the experimental sample rather than an effect of word length as was claimed. In the same manner, the da Costa Pinto (1991) and the Chincotta and Hoosain (1995) studies confounded mother tongue and language of instruction. Thus, no study to date has measured the effects of practice and exposure to digits arising from distinct linguistic experiences associated with the home and school.

In Experiment 1 the bilingual nature of Finnish society was used in order to examine the relationship between mother tongue, language of school instruction, and digit span using Finnish-Swedish bilinguals. The majority of Finns are Finnish speaking with approximately 6 per cent of the population classified as Swedish speaking (Brunell & Linnakylä, 1994). The city of Turku, from which the present sample was taken, is a microcosm of the national situation and consequently members of the SS bilingual type receive substantial exposure to Finnish in many aspects of life outside the home and school environs. Separate education provision for each language encompasses the range from kindergarten to university and fosters distinct linguistic experiences for both Finnish- and Swedish- speaking Finns. Children are taught Finnish as a second language in Swedish-medium schools and vice-versa. In addition, intermarriage between linguistic populations creates a wide diversity of, what we term, bilingual types. That is, there exist bilinguals fluent in the same languages but with different linguistic backgrounds and experiences. These features of Finnish bilingualism allowed both tighter control over the variables under discussion than previous studies and examination of the relative effects of practice arising from the language of the home, language of school, and cross-linguistic differences in word length for digit names on bilingual digit span.

The language of the home and language of schooling were varied orthogonally to create four distinct bilingual types. Two types had an identical mother tongue and language of schooling, either Swedish (SS) or Finnish (FF) and formed a category described as constant bilinguals. The two remaining types attended schools where the medium of instruction was a different language to that spoken in the home. For one group Swedish was the language of the home and Finnish the language of the school (SF) and vice versa (FS). These types were categorised as compound bilinguals. The manipulation of these variables allowed separate examination of the effects of language of the home and school factors as well as variation in performance according to bilingual type on digit span.

The relationship between digit span, numeral reading time and bilingual type was also investigated. A larger digit span was expected in the language in which a shorter reading time was obtained (Baddeley, 1990). Self-ratings of language ability have been used as a measure of competence between languages and to interpret whether differential digit spans may be attributable to the effects of word length or level of familiarity (e.g., Ellis & Hennelly, 1980). Similar self-ratings were obtained in order to examine the relationship between this variable and performance in reading rate and digit span across bilingual types.

Using number of syllables as approximate measures of digit name length, there existed a possibility that differences in articulation rate for digit names would be present between Finnish and Swedish. The average number of syllables per digit is 2.33 and 1.11 for Finnish and Swedish respectively (Appendix 2.1). Word length differences were examined by comparing reading time and digit span performance in the dominant language between constant bilinguals.

When rehearsal is suppressed by concurrent articulation, differences in word length are consistently abolished for both monolinguals (e.g., Baddeley, Lewis & Vallar, 1984) and bilinguals (Ellis & Hennelly, 1980) although this may occur only when a high level of proficiency in both languages is present (Chincotta & Hoosain, 1995). It was, thus, predicted that suppression would eliminate differences in digit span between languages for all four bilingual types, given that the present subjects were expected to display a relatively high level of bilingual functioning.

Three hypotheses were, therefore, put under test. Namely, are bilingual span effects due to differential levels of familiarity and practice arising from experiences associated with the language of home, language of school, or by cross-linguistic differences in word length?

2.3: EXPERIMENT 1

2.3.1: Method

Subjects

The subjects were 64 Finnish-Swedish bilingual students (30 males and 34 females) attending either Åbo Akademi, the Swedish-speaking university located in Turku, or Turun Yliopisto, Turku's Finnish-speaking university, who volunteered to participate in the experiment. An attempt was made to ensure that only subjects who had received all their schooling in the same language were selected for testing. This criterion was met by all with the exception of one female subject in the SF group who received the first nine years of schooling in Finnish and the remaining four in Swedish.

Materials

For the measurement of reading time, two lists of 200 random Arabic numerals varying from 1 to 9 were constructed. Although reading rate is not a pure quantification of articulation rate as this measure is sensitive to reading speed and familiarity with the stimuli. However, most of the bilingual digit span studies reported to date have made use of this measure as a replacement for more accurate estimations of articulation rate. In order to facilitate comparability between studies, we opted to use reading rate measures in the same manner.

Each number occurred with the same frequency in all four lists, ranging from 21 to 24 occurrences. Consecutive repetition of the same stimuli, and ascending and descending sequences of more than two numerals were avoided. Each list was printed in 20 rows each containing 10 numbers.

For the measurement of normal and suppressed digit span in both languages, four sets of sequences of random digits varying from 1 to 9 were prepared. Each set commenced with two, 2 digit sequences, followed by two, 3 digit sequences, and so on to a maximum of two, 13 digit sequences. Identical items appearing contiguously and ascending and descending sequences were avoided. The lists were presented via computer in Arabic numeral form at the rate of one digit per second. Each successive numeral appeared in the same position on the screen. Prior to and subsequent to presentation of the sequence, a series of four tones was generated by the computer program at the rate of one tone per second, after which the legend RECALL appeared on the screen prompting subjects to commence verbal recall. Instructions for the reading time and digit span measures were prepared in both Swedish and Finnish.

<u>Procedure</u>

Subjects were tested individually by a fluent bilingual who identified the mother tongue and language of school instruction. On the basis of responses, subjects were assigned to either Swedish mother tongue, and language of instruction (SS), or Finnish mother tongue and language of instruction (FF) groups. Two further groups were composed of subjects who reported Finnish as their mother tongue and Swedish as the language of school instruction (FS) and vice versa (SF). Each group contained 16 subjects and equal numbers of male and female subjects except in the case of SF (male = 6, female = 10). From this point, all discourse with subjects was conducted in either Swedish or

Finnish. Language of instruction was varied and counterbalanced, half the Finnish mother tongue subjects received instructions in Swedish and the other half in Finnish and vice versa.

Subjects were asked to self-rate their own competence in each language on a 1 - 10 point scale. Subjects provided a self-rating for their most proficient language and then self-rated competence in the least proficient language in relation to the first.

Measures of reading time for 200 numerals were taken in both Swedish and Finnish. Subjects read the lists accurately and as quickly as possible, pronouncing each digit individually and audibly. List order was counterbalanced by Latin square and time taken measured by stop watch.

Next, digit span with and without suppression in both languages was measured. Random numerals were presented using a computer, each condition commenced with two 3-digit sequences, two 4-digit sequences, and so on, to a maximum of 15 digits. Both control and suppression conditions included a 4 second delay before the command prompting recall appeared on the screen. In the condition measuring suppressed recall, concurrent articulation consisted of audible and continuous repetition of the neutral sound la-la four seconds prior and subsequent to presentation of the stimuli. Subjects were prompted to begin and terminate suppression with tones generated by the computer. For each condition, the subjects continued recalling digit sequences verbally until two incorrect responses were made, upon which testing terminated.

Before testing, subjects were allowed two practice trials using the suppression phrase to ensure speed of articulation was approximately two phrases per second. Digit span was operationalised as the length of the last correctly recalled sequence. If both sequences at the last sequence length were correct a score of 0.5 was added. The language of practice was varied and the digit span lists were counterbalanced by a Latin square.

2.3.2 Results

Self-Rating

Data from the self-ratings of competence in either Finnish or Swedish were subjected to a two-way analysis of variance, in which bilingual type (FF, FS, SF, or SS) was a between subjects factor and self-rating was a within subjects factor and is summarised in Figure 2.1.

This showed a reliable effect of bilingual type (F (3,60) = 4.96, $p < .01$), and of self-rating (F (1,60) = 25.01, $p < .0001$) with self-rating for Finnish (8.88) higher than Swedish (8.45). The interaction between type and self-rating was also reliable (F (3,60) = 65.19, $p < .0001$). Simple main effects reveal that FF, FS and SF rated competence in Finnish higher than Swedish (F (1,60) = 76.30, $p < .0001$, F (1,60) = 41.64, $p < .0001$ and F (1,60) = 16.81, $p < .001$ respectively). Only SS self-rated greater competence in Swedish (F (1,60) = 85.92, $p < .0001$).

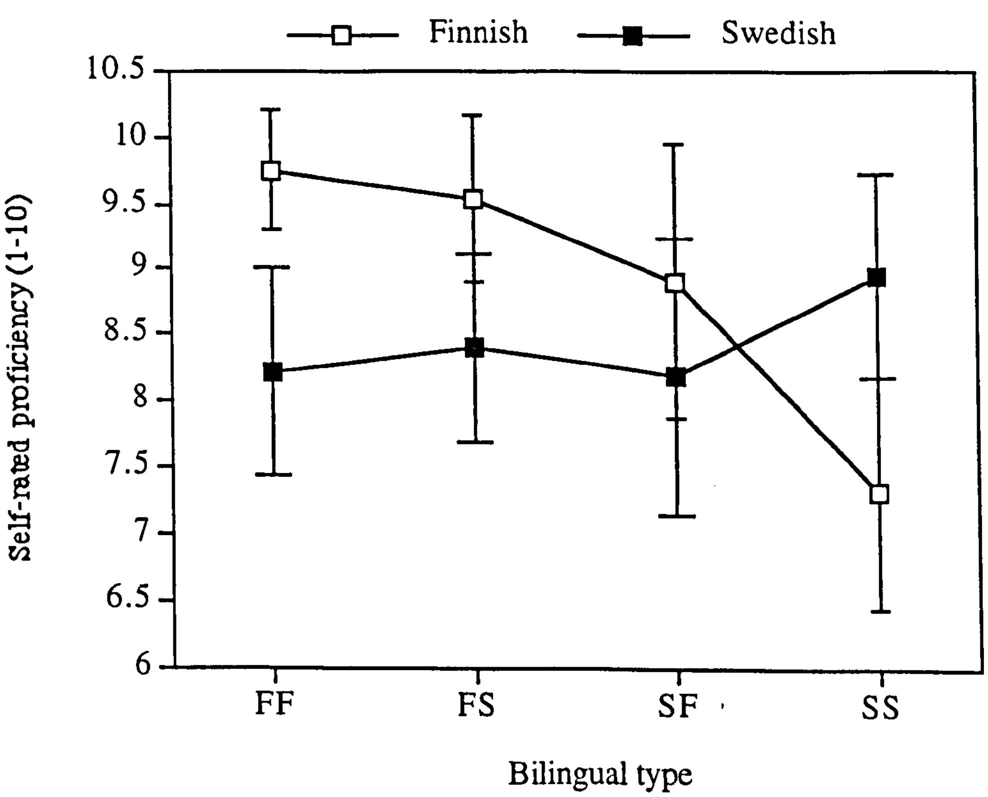

Figure 2.1: Mean self-rated proficiency in Finnish and Swedish (1-10) by four bilingual types.

Pairwise comparisons using Tukey tests showed that ratings for Finnish by FF were significantly higher than those for SS ($p < .01$), and SF ($p < .05$). FS and SF, in turn, self-rated higher competence in Finnish than SS (both $p < .01$). Self-ratings for Swedish were significant only between SS (8.94) and SF (8.19) ($p < .05$).

These results indicated that three groups (FF, FS, & SF) rated themselves as more proficient in Finnish while only the SS group rated themselves as more proficient in Swedish Thus, according to self-ratings, no group was balanced in terms of bilingual proficiency.

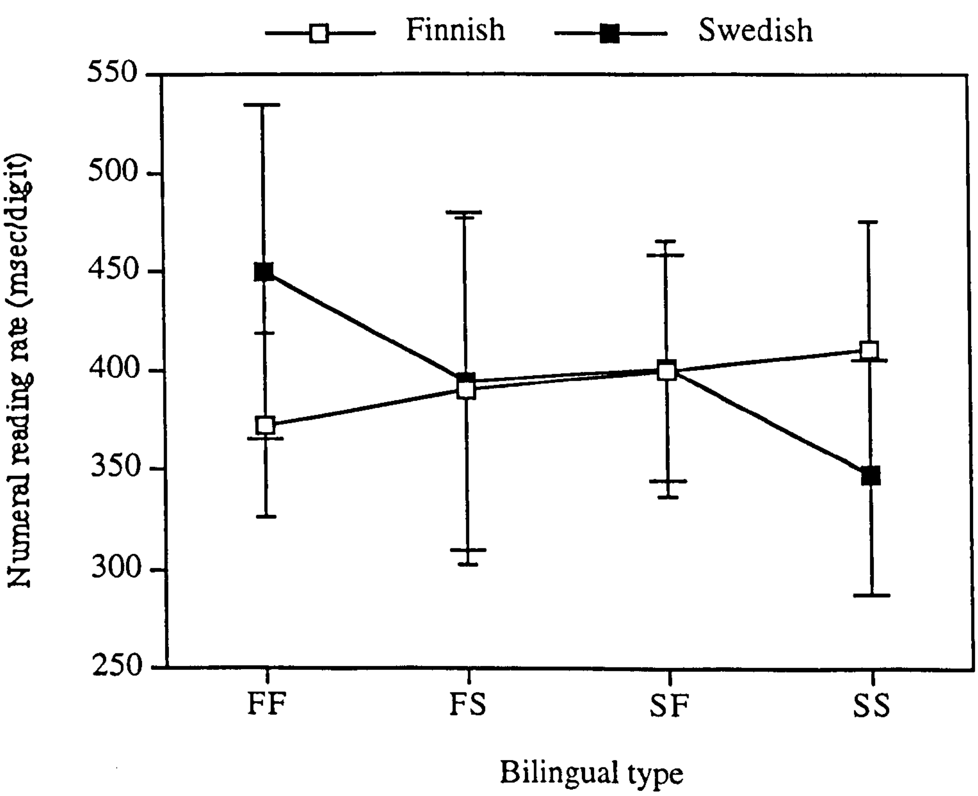

Figure 2.2: Mean numeral reading time (msec/digit) in Finnish and Swedish for four bilingual types.

Reading Time

The data from the 200 numeral reading task in Finnish and Swedish were converted into measure of reading time (msec/digit). These data were subjected to a three-way analysis of variance in which mother tongue and language of schooling were between-subjects factors and language (Finnish or Swedish) was a within subjects factor and are summarised in Figure 2.2.

None of the main effects were reliable but significant interactions were revealed between mother tongue and language (F (1,60) = 47.52, p < .0001) and language of schooling and language (F (1,60) = 42.73, p < .0001). Analysis of the interaction between mother tongue and language by simple main effects indicated that Finnish mother tongue speakers read faster in Finnish compared to Swedish (F (1,60) = 30.53, p < .0001, means = 382 and 423 msec/digit respectively) and Swedish mother tongue speakers read faster in Swedish than Finnish (F (1,60) = 17.83, p < .001, means = 374 and 406 msec/digit respectively). A difference was present between Finnish and Swedish mother tongue speakers for reading time performance in Swedish (F (1,60) = 7.72, p < .01, means = 423 and 374 msec/digit respectively) but not Finnish.

Analysis of the interaction between language of schooling and language by simple main effects indicated that subjects taught through the medium of Finnish read faster in Finnish than in Swedish (F (1,60) = 27,81, p < .0001, means = 387 and 426 msec/digit respectively), whereas those taught via Swedish read faster in Swedish than in Finnish (F (1,60) = 15.77, p < .0001, means = 371 and 400 msec/digit respectively). A difference was present between Finnish and Swedish language of schooling subjects for reading time performance in Swedish (F (1,60) = 10.06, p < .01, means = 426 and 371 msec/digit respectively) but not in Finnish.

The results of two-way interactions, thus, showed that both the mother tongue and language of schooling factors were associated with performance on the reading task. The absence of a higher-order interaction (F (1,60) = .072) indicated that reading time performance did not vary across each bilingual type. Inspection of the means, however, strongly suggested both a difference between SS and FF for when performance was specified in Swedish and variation in between-language performance as a function of bilingual type. In order to examine whether a lack of power in the design may have resulted in the statistical suggestion that performance across the bilingual types was equivalent, the data were further subjected to a separate two-way analysis of variance in which bilingual type was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor.

This showed that the main effects of bilingual type and language were not reliable but the interaction between the factors was (F (3,60) = 30.11). Analysis of the interaction by simple main effects indicated a between-language difference in reading time for FF (F (1,60) = 53.42, $p < .0001$) and SS (F (1,60) = 37.46, $p < .0001$). In each case reading time was shorter in the dominant language, i.e., FF read faster in Finnish compared to Swedish (means = 373 and 450 msec/digit respectively) and SS read faster in Swedish compared to Finnish (means = 347 and 411 msec/digit respectively). Neither compound bilingual type (FS or SF) showed any differences in reading time between languages. A difference across bilingual type was present when performance was specified in Swedish (F (3,120) = 5.926, $p < .001$) but not for Finnish ($F < 1$).

To summarise, a shorter reading time was associated with both mother tongue and language of schooling: numeral reading time tended to be fastest in both the mother tongue and in the language in which schooling was received. However, the most important finding in this respect was that this relationship varied according to bilingual type. Constant bilinguals performed fastest in their more dominant language (i.e., language of the home and school), whereas compound bilinguals showed no difference between languages on this measure. A finding of some interest was that the consequence of differential mother tongue and language of schooling experiences specifically affected reading time performance in Swedish rather than Finnish. Subjects with Swedish as either a mother tongue or language of school instruction performed significantly better in Swedish compared to Finnish counterparts, whereas no differences were observed for performance in Finnish regardless of the effects of these factors.

Digit Span

The data from the digit span tasks in Finnish and Swedish were subjected to a three-way analysis of variance, in which mother tongue and language of schooling were between-subjects factors and language (Finnish or Swedish) was a within-subjects factor and are summarised in Figure 2.3. None of the main effects were significant, but interactions between mother tongue and language (F, (1,60) = 8.45, $p < .01$) and language of schooling and language (F, (1,60) = 21.92, $p < .0001$) were reliable. The higher order interaction was not reliable ($F < 1$).

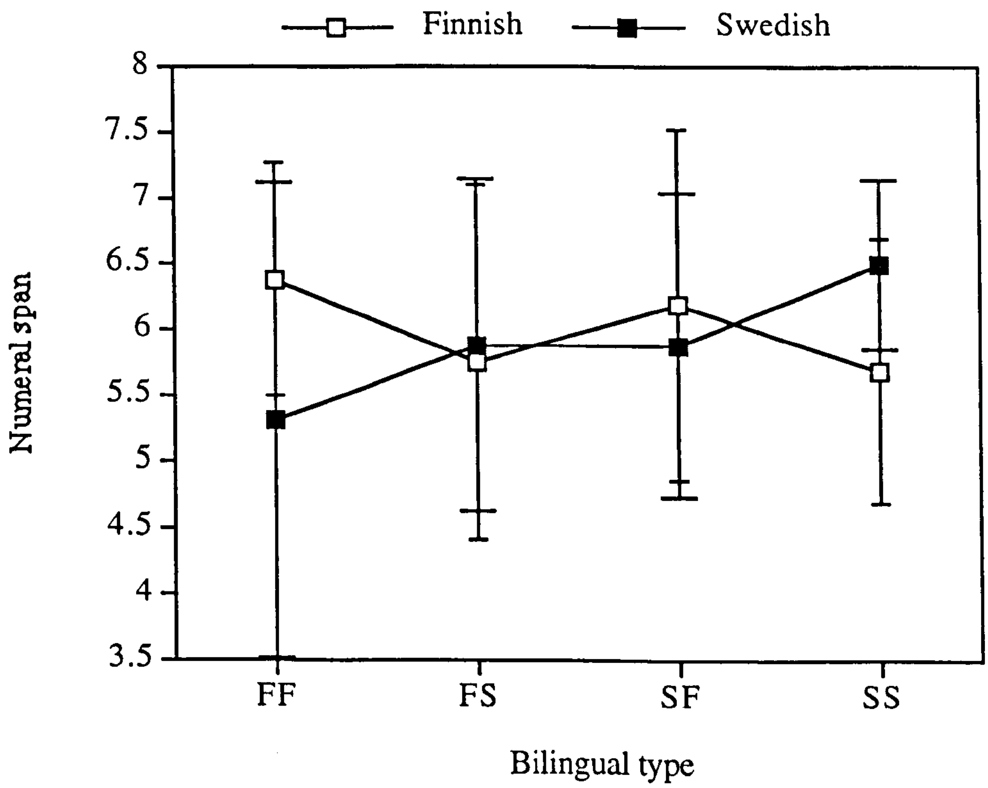

Figure 2.3: Mean numeral span under the silent recall condition for four bilingual types.

Analysis of the interaction between mother tongue and language by simple main effects revealed between language differences in span for Finnish mother tongue subjects (F, (1,60) = 7.20, $p < .01$, means Finnish = 6.06, Swedish = 5.59). No differences in span were present for Swedish mother tongue subjects. Within language comparison of span between Finnish and Swedish mother tongue speakers revealed a difference for Swedish (F, (1,60) = 4.72, $p < .05$, means 5.59 and 6.19 respectively) but not Finnish.

Analysis of the interaction between language of schooling and language by simple main effects revealed between language differences in span for Finnish schooled subjects (F, (1,60) = 15.50, $p < .001$, means Finnish = 6.28, Swedish = 5.59) and Swedish schooled subjects (F, (1,60) = 7.20, $p < .01$, means Finnish = 5.72, Swedish = 6.19). Within language comparison of span between Finnish and Swedish schooled subjects revealed a difference for Swedish (F, (1,60) = 4.72, $p < .05$, means 5.59 and 6.19 respectively) and Finnish (F, (1,60) = 4.23 $p < .05$, means 6.28 and 5.72 respectively).

The data were further subjected to a separate two-way analysis of variance in which bilingual type was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor. This revealed that no main effects of bilingual type or language were present but the interaction between the factors was reliable (F (3,60) = 10.133, $p < .0001$). Analysis of the interaction by simple main effects indicated a between-language difference for Finnish and Swedish constant bilinguals (FF, F, (1,60) = 18.51, $p < .001$, means Finnish = 6.38, Swedish = 5.31; SS, (F, (1,60) = 10.82, $p < .01$, means Finnish = 5.69, Swedish = 6.50). No between-language differences in digit span were present for the compound bilinguals. Within-language performance varied as a function of bilingual type for Swedish (F (3,120) = 3.148, $p < .05$) but not Finnish (F (3,120) = 1.498, $p > .05$).

To summarise, when digit span performance between mother tongue and language of schooling factors was compared, the trends were broadly similar with some important exceptions. Finnish mother tongue speakers obtained reliably greater spans for Finnish whereas Swedish mother tongue speakers performed equally in both languages. Additionally, although Swedish mother tongue speakers obtained larger digit spans than their Finnish counterparts for Swedish, the reverse was not true. Swedish schooled subjects obtained larger spans in Swedish compared to Finnish schooled subjects and vice versa, and within language differences in digit span between groups were all reliable. These findings suggested that language of schooling was consistently related to the language in which larger digit span was obtained.

Given that the mother tongue and language of schooling factors contained composite data from both compound and constant bilinguals it seemed judicious to analyse digit span performance according to bilingual type. This revealed that both groups of constant bilinguals were found to obtain greater digit spans in their dominant language, whereas both groups of compound bilinguals performed equally in both languages despite having self-rated higher proficiency in Finnish.

Numeral reading time proved a reliable predictor of digit span performance according to bilingual type. A relationship was observed between numeral reading time and digit span, with larger digit span associated with the language in which numeral reading performance was fastest. In the case of compound bilinguals, a lack of difference in numeral reading time between languages predicted a similar relationship between Finnish and Swedish digit span. Pearson coefficients confirmed the relationship between numeral reading time and digit span for both languages (Finnish = -.38 ($p < .01$, Swedish = -.36 ($p < .01$). A negative value indicated faster reading time was related to larger digit span.

Articulatory Suppression

The data from Finnish and Swedish digit span tasks under articulatory suppression were subjected to a three-way analysis of variance, in which mother tongue and language of schooling were between-subjects factors and language (Finnish or Swedish) was a within subjects factor and are summarised in Figure 2.4. None of the main effects or interactions were reliable. The results were straightforward, articulatory suppression eliminated the between-language difference for the FF and SS bilingual types.

The evidence presented thus far revealed the effects of proficiency arising from both mother tongue and language of schooling on bilingual digit span. The magnitude of these effects on digit span appeared to mask any possible effects arising from word length differences between Finnish and Swedish. Nonetheless, there was some support for the view that the processes underlying bilingual memory span for digits is language-based in the finding that articulatory suppression abolished the between language differences for constant bilinguals. However, it remained unclear whether a lack of difference between digit span measures for compound bilinguals was a result of a highly balanced level of bilingualism or whether a hypothesised word length advantage for Swedish was compensating for lower proficiency in Swedish. Given that both groups of compound bilinguals self-rated higher proficiency in Finnish over Swedish, this possibility could not be discounted.

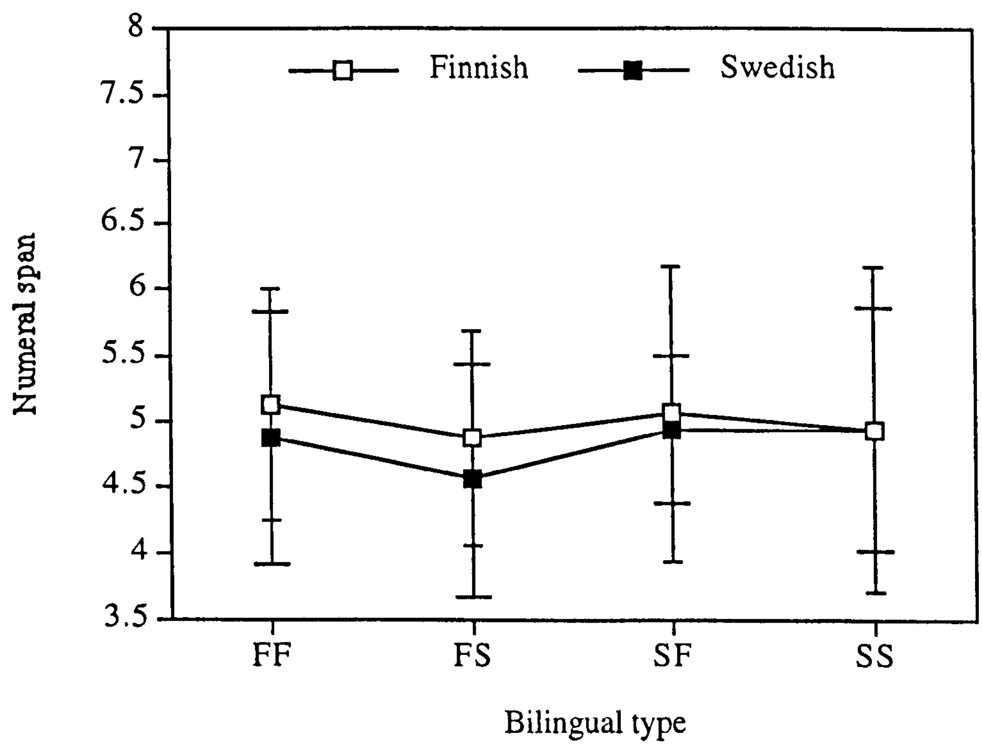

Figure 2.4: Mean numeral span under articulatory suppression for four bilingual types.

In order to examine the possible effects of word length on digit span, the data were subjected to a series of post hoc analyses. A sample of ten, highly balanced, compound bilingual subjects was selected on the basis of self-ratings. The selection procedure resulted in 10 compound bilingual subjects being chosen (5 FS and 5 SF).

Self-ratings for SF subjects (SFS) were matched equally. Four FS subjects (FSS), self-rated higher proficiency in Finnish by a margin of 0.5. The remaining subject self-rated higher proficiency for Finnish by a margin of 0.1. A Wilcoxon matched pairs test revealed that the difference in self-rating between languages overall was not significant (means Finnish = 9.05, Swedish = 8.84).

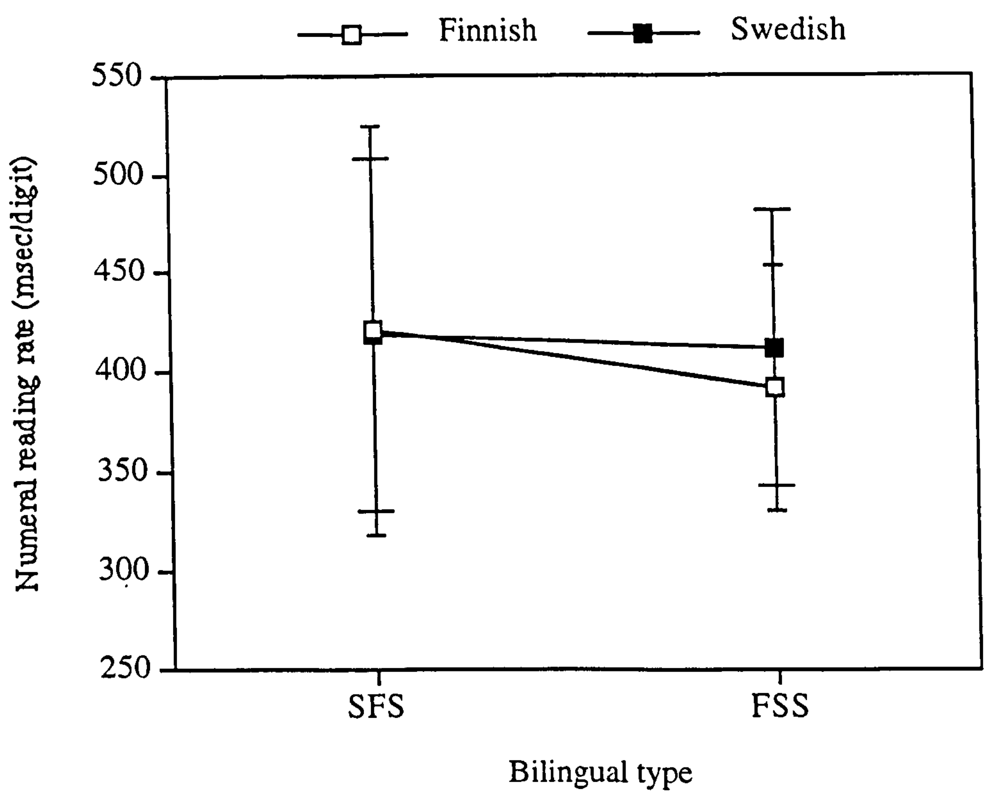

Figure 2.5: Mean reading time (msec/digit) in Finnish and Swedish by two groups of highly balanced bilinguals.

The numeral reading time data were subjected to a two-way analysis of variance, in which bilingual type (FSS or SFS) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor and are summarised in Figure. 2.5 . This revealed no reliable main effects or interaction between the two factors.

The digit span data were subjected to a two-way analysis of variance, in which the factors were bilingual type and language and are summarised in Figure 2.6. This showed a significant effect of language ($F(1,8) = 6.00$, $p < .05$), but no significant effect of bilingual type and no significant interaction. Observation of the means for Finnish and Swedish digit span indicated larger digit span in Swedish (means 5.3 and 5.9 respectively). Pairwise comparisons using Tukey tests revealed a difference in span for the FSS bilingual type (Finnish = 5, Swedish = 6) but not for SFS.

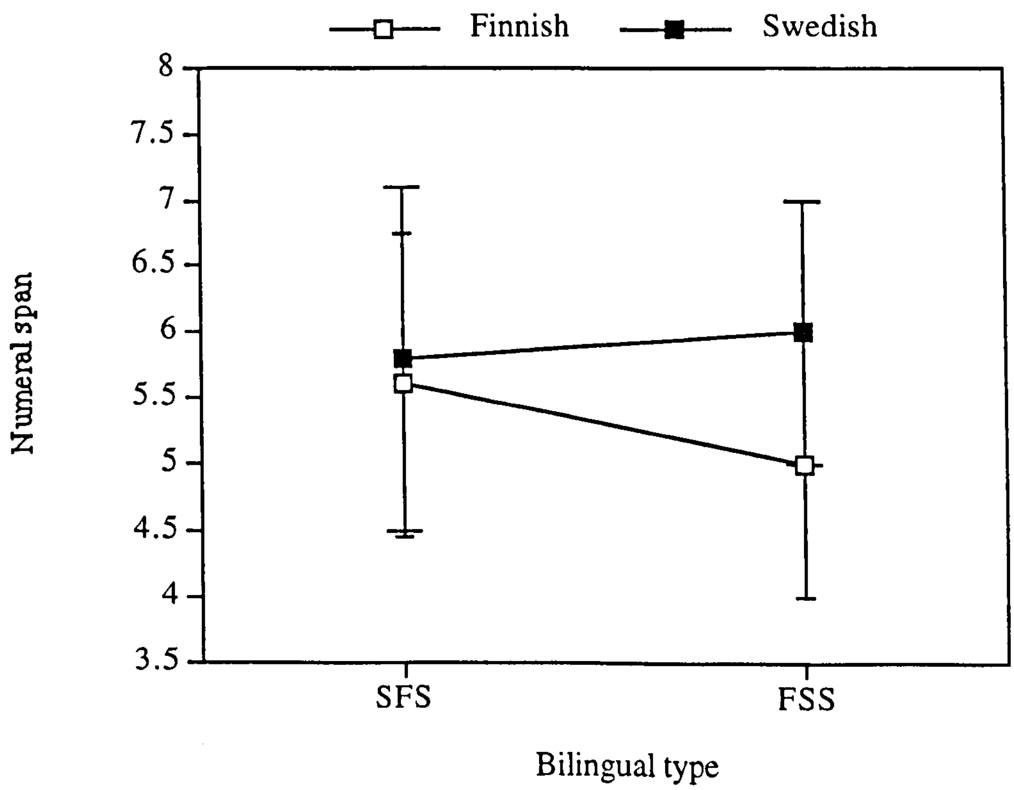

Figure 2.6: Mean digit span in Finnish and Swedish by two groups of highly balanced bilinguals.

To summarise, the results of the post hoc analyses showed digit span performance was greater in Swedish than Finnish for the FSS bilingual types. Given that FSS subjects consistently, if only marginally, self-rated higher proficiency in Finnish, the difference in digit span may reasonably be interpreted as an effect of a word length advantage in favour of Swedish.

Two points are worthy of mention. First, it should be noted that the effects of language of schooling may be equally responsible for the observed digit span difference for FSS subjects in the post hoc analysis. However, for SFS, the language of schooling effect cannot account for the lack of difference between Finnish and Swedish digit span. It is possible that for SFS the expected higher level of proficiency in Finnish arising from schooling in the same language was, to some extent, attenuated by the word length advantage for Swedish. This could explain the lack of difference in digit span observed for this group. For SFS, an alternative source of practice and exposure to Swedish, incapable of being identified in the present study, might be present.

Second, although the results of the analysis of variance conducted on numeral time scores did not predict digit span performance in the post hoc analysis, some evidence of an association between numeral reading time and digit span was obtained from the results of Pearson correlational analyses. Here, Finnish and Swedish numeral reading time correlated highly and significantly with Finnish and Swedish digit span respectively (- 0.71, $p < .05$ and - 0.63, $p = .05$ respectively).

Digit Word Reading Time.

In addition to the numeral reading task, a pilot study involving a digit word reading task for 200 items by the same subjects was conducted as a basis upon which to plan further work. These measures were obtained to compare the between-language estimates of word length yielded by numeral (i.e., 1, 2, & 3, etc.) and digit word (i.e., one, two, & three, etc.) representations of digits. It was reasoned that the availability of lexical support for the digit word stimuli would result in measures of reading time that were less influenced by familiarity with the language than for the language-neutral, numeral stimuli.

These data were subjected to a two-way analysis of variance in which bilingual type was a between-subjects factor and language was a within-subjects factor and are summarised in Figure 2.7. The results showed a main effect of language ($F(1,60) = 137.71$, $p < .0001$) with a faster reading time for Swedish than Finnish (means = 363 and 406 msec/word respectively) and the interaction between the factors was reliable ($F(3,60) = 6.37$, $p < 0.001$). Analysis of the interaction by simple main effects indicated no within-language difference for either Finnish (F (3,120) = 1.64, $p > 0.05$) or Swedish (F (3,120) = 1.20, $p > 0.05$).

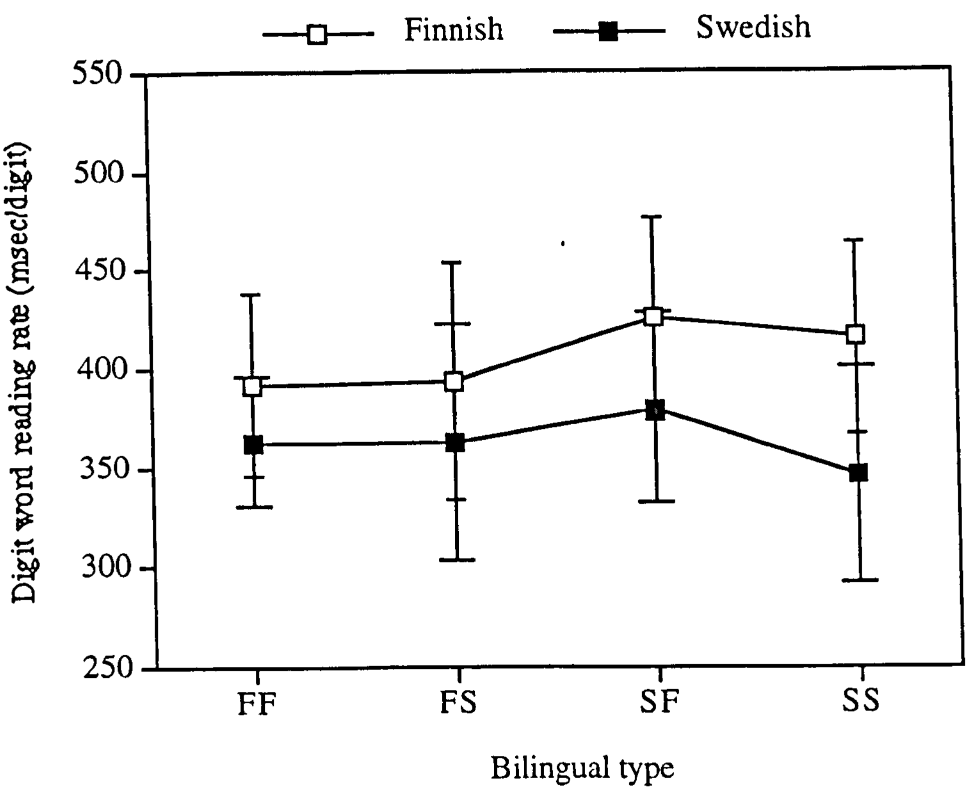

Figure 2.7: Mean digit word reading time (msec/digit) in Finnish and Swedish for four bilingual types.

A between-language difference was present for all bilingual types (all F (1,160) > 15, $p < 0.001$) with reading time consistently faster for Swedish than Finnish. The magnitude of the effect was greater for the SS group (F (1, 60) = 87.98) than for the remaining bilingual types (F = FF = 15.92, FS = 16.60, SF = 36.32), and hence the interaction term.

To summarise, the results of the digit word reading task showed that when the stimuli were represented as digit words as opposed to Arabic numerals, reading time was consistently faster in Swedish than Finnish regardless of bilingual type. Interestingly, performance did not vary as a function of bilingual type for either Swedish or Finnish. This finding, raised the interesting possibility that the language relationship in bilingual digit span performance could vary as a function of digit representation (i.e., numerals or digit words). This question was addressed in a series of subsequent experiments and reported in Chapters 6-8.

2.3.3: Discussion

Experiment 1 examined whether bilingual span effects were associated with levels of practice arising from two obvious sources, namely, the languages of the home and school or whether differences could instead be attributed to variation in digit name word length between languages.

The hypothesis predicting greater digit span in the language of school instruction initially appeared to be supported as there were consistently larger digit spans in the language in which subjects received their education. The results as a function of mother tongue, on the other hand, were less consistent. Although Finnish mother tongue speakers obtained larger digit spans in Finnish, performance by Swedish mother tongue speakers was equal in both languages. These findings suggested that digit span tended towards being greatest in the language of school instruction rather than in the language of the home. A result anticipated by Naveh-Benjamin and Ayres (1986) based on the view that massive levels of practice in counting and computation associated with schooling were likely to result in a higher level of familiarity with digits compared to the language of the home.

This level of analysis, however, concealed important differences in performance by bilingual types. When digit span performance was examined according to these groupings, both sets of compound bilinguals performed equivalently in Finnish and Swedish, regardless of the language in which schooling was received, whereas, constant bilinguals obtained larger digit spans in the dominant language. These findings mirrored numeral reading time performance exactly and a relationship between numeral reading time and digit span was observed with larger digit span associated with the language in which numerals were read faster, as would have been predicted by working memory theory. In the case of compound bilinguals, a lack of difference between languages in numeral reading time predicted a similar relationship between Finnish and Swedish digit span.

Articulatory suppression abolished language differences for constant bilinguals and impaired digit span for both languages significantly for compound bilinguals. Compound bilinguals continued to show no differences between languages for suppressed digit span and no differences were present for between bilingual types for either language. According to working memory theory, the elimination of digit span differences confirms that the processes underlying memory span are speech based. These findings also supported Chincotta and Hoosain's (1995) suggestion that the effects of suppression are consistent in abolishing digit span differences between languages when a high level of bilingual competence is displayed.

It would be premature to conclude, however, that the lack of bilingual span effects observed for compound bilinguals was simply the result of extensive exposure to both languages experienced by these individuals given the possibility of an interaction between word length differences in Finnish and Swedish and the language of home and school factors. Evidence of this possibility was obtained from the results of post hoc analysis on a sample of highly balanced compound bilinguals. This showed that subjects with a higher self-rating for Finnish who attended Swedish-medium schools obtained larger digit spans in Swedish. Although this result may be interpreted as an effect of either language of schooling or word length, the question remained as to why similarly highly balanced compound bilinguals attending Finnish-medium schools did not perform better in Finnish than Swedish. One likely explanation was a possibility that a word length advantage for Swedish attenuated the expected larger digit span for Finnish for Finnish-educated, compound bilinguals.

Although the magnitude of the effect of language of schooling was strong, the pervasive effect of cross-linguistic differences in word length cannot be dissociated from performance on bilingual digit span and indeed seems to underlie the phenomenon. This claim was made even though the identification of cross-linguistic differences proved more difficult than we anticipated (probably due to a tendency to abbreviate the relatively unwieldy words for Finnish digits to shorter, conventionally accepted equivalents).

In summary, the present findings suggested that compound and constant bilinguals behaved in substantially different ways. Constant bilinguals performed best in their more dominant language, whereas compound bilinguals, due to their more diverse linguistic background, achieved equivalent digit spans in both languages. The effect of practice in processing digits associated with schooling was, thus, not sufficient to ensure that performance in digit span was favoured in the language of instruction. Factors, other than the language of schooling, that contributed toward this high level of competence in both languages by compound bilinguals were not identified in the present study, although there existed a strong possibility that a word length advantage for Swedish digit names may have been partly responsible for the observed balance in performance.

Two further points needed to be made. First, the present results applied only to bilinguals who had completed schooling, and were embarked upon undergraduate careers. Half of the present subjects could be described as having successfully negotiated schooling in a second language. It was considered that a further study of bilingual digit span performance as a function of year of schooling would provide some indication of effect of such educational experiences. The effects of practice and familiarity associated with schooling upon bilingual digit span functioning could then be traced in a more comprehensive manner.

Second, given that Finnish is the more pervasive language, all Finns (whether Finnish or Swedish speaking) are likely to receive broad exposure to Finnish. This resulted in a higher level of general competence in Finnish overall, even for the SS bilingual type who would naturally receive less exposure to Finnish in the home and school than other bilingual types. Correspondingly, FF bilinguals would receive less exposure to their second language (Swedish) than the remaining bilingual types. There existed that possibility that the particular juxtaposition and status of the Finnish and Swedish languages within Finland may have been an important variable affecting performance. This prospect could be further investigated by comparing performance by Swedish-Finnish bilinguals resident in Sweden.

Finally, one finding was clear, the lack of homogeneity in performance between bilingual types cautions against the indiscriminate selection and pooling of bilingual types within any experimental sample. When examining aspects of bilingual information processing, due consideration must be given to bilingual diversity and the effects that differential linguistic experiences may have on performance even within the same bilingual pairing.

Chapter 3

Speech Rate Estimation and Bilingual Digit Span Development

The findings of Experiment 1 suggested that for Finnish-Swedish bilinguals larger digit span was associated with the language in which schooling was received rather than the mother tongue (language of the home). A more detailed analysis of the results according to bilingual type, however, indicated that the language of schooling hypothesis did not account for the full range of results as here the compound bilingual types (FS and SF) obtained an equivalent digit span in Finnish and Swedish. The findings that performance on the numeral reading task predicted performance on the memory span task and that articulatory suppression eliminated language differences supported the view that the bilingual digit span effect was moderated by speech rate and phonological loop functioning. In the next study, two issues arising directly from the findings of Experiment 1 were examined further.

Firstly, the finding that all four bilingual types in Experiment 1 consistently read digit words faster in Swedish than Finnish, whereas the between-language relationship on the numeral reading task varied as a function of bilingual type suggested that the method of speech rate estimation, and the manner in which digits are represented were variables of some importance in determining the outcome of bilingual digit span tasks.

Secondly, given that the language of schooling was identified as an important, though not exclusive, determinant of bilingual digit span it was appropriate to trace the relationship between the languages as a function of years of schooling. In particular, the post hoc analysis of a sample of highly balanced FS bilinguals indicated that for this group of individuals the language in which schooling was received was a reliable predictor of bilingual digit span performance. A developmental study would, therefore, allow the tracing of the impact of schooling on the relationship on digit span for this bilingual type. In addition, a comparison between FS and SS bilinguals would allow the examination of the effect of receiving schooling in a second language on digit span compared to native speakers of the language of the curriculum.

3.1: Speech Rate Estimation

The finding in Experiment 1 that the between-language performance on the reading time task varied across bilingual types as a function of whether the stimuli were represented as numerals or digit words raised the possibility that the use of numeral stimuli in bilingual digit span studies (Ellis & Hennelly, 1980; da Costa Pinto , 1991; Chincotta & Hoosain, 1995) may have been injudicious). Although the relationship between various measures of speech rate and memory span has been examined in monolinguals (Tehan & Humphreys, 1988; Henry, 1994), the question as to the most appropriate way of estimating speech rate in bilinguals, however, has been left open. Experiment 2 examined the power of three estimates of speech rate in predicting bilingual digit span and compared performance by native and non-native speakers of the language of schooling.

A central assumption of working memory theory is that the rate of subvocal rehearsal is adequately indexed by overt speech rate. Support for this notion is provided by the linear relationship between speech rate and memory span found in both adults (Baddeley et al., 1975) and children (Nicholson, 1981), and correlations between the factors (Standing & Curtis, 1989). Evidence of a causal relationship between speech rate and memory span was obtained by Hulme, Thomson, Muir and Lawrence (1984), Hulme and Muir, (1985), and Henry and Millar (1991). These studies have demonstrated that memory capacity remains constant after early childhood and that developmental increases in span are occasioned by faster rates of speech. Henry and Millar (1991), however, found that the relationship between memory span and speech rate was observed when the latter was estimated by the maximal articulation of groups of words rather than individual ones. The manner in which speech rate is estimated, thus, appears to be a variable of some consequence.

Speech rate has been estimated by various means including the measurement of single word utterances (Caplan, Rochon, & Waters, 1992), rapid repetition of pairs or triplets of words (Hitch, Halliday, & Littler, 1989), oral (Hitch et al., 1989) and whispered (Standing & Curtis, 1989) reading of word lists. Furthermore, attempts have been made to estimate the rate of subvocalization more directly by measuring silent reading rate (Standing & Curtis, 1989) and silent rehearsal of word pairs (Baddeley & Andrade, 1994). The introspective nature of such tasks, however, raises serious doubts about the validity of attempts to obtain direct estimates of subvocal rehearsal (Caplan & Waters, 1994).

Several studies have questioned whether speech rate adequately indexes the rate of subvocal rehearsal or whether it is related to other variables affecting memory span. Cowan, Day, Saults, Keller, Johnson, and Flores (1992) and Henry (1991), for example, have argued that word length effects may be largely accounted for by output delays rather than subvocal rehearsal and that speech rate affects the speed at which recall is effected.

Memory span has been demonstrated to be sensitive to factors other than the articulatory duration of items. Hulme, Maughan, and Brown (1991), Roodenrys, Hulme, and Brown (1993), and Hulme, Roodenrys, Brown, and Mercer, (1995), for example, have shown that factors independent of speech rate, such as the strength of long term memory representations, are related to memory span. Additionally, Case, Kurland, and Goldberg (1982) and Kail (1992) have argued that developmental increases in memory capacity may be due to improvements in operational efficiency, whilst Dempster (1981) has posited that the effects of word length on memory span may be accounted for in terms of differences in item identification with short words identified faster than long words.

Hitch, Halliday, and Littler (1989) compared the relationship between memory span and articulation rate, reading rate, auditory and visual item identification latencies.

Articulation rate and reading rate were found to be highly correlated with visual memory span (both r = .97), whereas visual and auditory item identification times were highly correlated with suppressed memory span (r = -.96 and -.89 respectively). Of the speech rate measures, only reading rate correlated with suppressed memory span (r = .84): some indication that, although related, reading rate and articulation rate indexed different processes. Reading rate and visual item identification were differentially related to memory span, thus, Hitch et al. (1989) concluded that reading rate was relatively unaffected by factors related to item identification. Nevertheless, although articulation rate and reading rate were found to be related equivalently with memory span Hitch et al. (1989) suggested that articulation rate was the most appropriate index of subvocal rehearsal.

The evidence described thus far identified speech rate as an influential determinant of memory capacity in monolinguals. Examining the relationship between memory capacity and speech rate in bilinguals, however, has proved less tractable than for monolinguals given the added variable of relative differences in fluency between the languages.

Previous studies of bilingual digit span have generally estimated the rate of subvocalization using reading tasks. While this would seem appropriate when digit span is measured in the visual modality (e.g., Chincotta & Hoosain, 1995) estimates of speech rate based on reading tasks have also been used when memory capacity is measured in the auditory modality (e.g., Ellis & Hennelly, 1980; da Costa Pinto, 1991). It seemed reasonable to suggest that the assumption that speech rate estimates involving reading are an adequate measure of differences in articulation duration between languages was injudicious given the likelihood that performance was likely to be affected by discrete levels of familiarity with the printed stimuli. Under these circumstances it was difficult to establish whether differential speech rates between languages are occasioned by variation in recognition processes, delays in planning the articulatory gestures required for speech or, ceteris paribus, actual differences in word length.

Two further problems are associated with the use of numeral representations in bilingual digit span tasks. First, language-neutral stimuli, as numeral stimuli are, would seem to be particularly prone to Stroop-type interference from the more proficient language when the task is performed in the less proficient language (e.g., Gerhand, Derçgowski, & McAllister, 1995). A second, related point is that the absence of lexical support for numeral stimuli results in reading rate and memory span measures that are heavily influenced by the relative level of competence between the languages (Chincotta & Hoosain, 1995). These possibilities questioned the validity of using numeral stimuli for the estimation of digit name word length in bilingual information processing studies particularly when memory span is measured in the auditory modality: a matter that was examined further in Chapter 5.

The problems associated with the use of inadequate speech rate estimates and complications arising from the use of distinct representations of number discussed thus far have made the interpretation of digit span studies difficult. To elaborate, in the Ellis and Hennelly (1980, Experiment 1) study, Welsh-English bilinguals with a higher self-rated proficiency in Welsh took longer to read numerals in Welsh compared to English and that a faster numeral reading rate for English predicted larger auditory digit span in this language compared to Welsh.

In a further experiment using a different sample of similar bilinguals, the finding that numerals were read faster in English then Welsh was replicated (Experiment 3a). However, when speech rate was estimated using digit word stimuli, reading rate was equivalent between the languages (Experiment 3b). Visual memory span for digit words under articulatory suppression was equivalent between Welsh and English, thus, Ellis and Hennelly (1980) attributed the language difference observed in Experiment 1 to the disparity in articulation durations for numerals between the languages.

Now, according to the working memory model digit word reading rate predicted equivalent digit spans between Welsh and English. Therefore, it is argued that the conclusion that articulatory suppression eliminated a hypothesised word length difference between Welsh and English was premature given that the crucial test of measuring memory span for digit word stimuli without articulatory suppression was not conducted.

A similar criticism can be made of Da Costa Pinto's (1991) study. Here speech rate was estimated by reading tasks for both numeral and digit word stimuli and the results indicated faster performance in Portuguese than English for both item sets. However, da Costa Pinto (1991) measured digit span in the auditory modality and obtained memory span measures for digit words under articulatory suppression in the visual modality. Thus, although memory spans were consistently larger in Portuguese and were predicted by faster reading rate for Portuguese, the crucial tests that would allow a clear interpretation of the effects, i.e., speech rate measures independent of reading or control measures of digit word memory span, were not conducted.

Elliot (1992) quantified speech rate by instructing subjects to memorise and repeatedly articulate digit sequences five times (5 digits in the case of children and 9 digits for adults). Elliot (1992) reported correlations between articulation rate and auditory digit span ranging from 0.37 to 0.45 for the collective sample consisting of four distinct language pairings. These collective correlation coefficients, however, disguised the relationship between articulation rate and digit span at the individual language level where English-Mandarin bilinguals obtained equivalent digit spans between the languages despite faster articulation in Mandarin than English.

So, it would appear that neither articulation rate nor reading rate (whether for numeral or digit word stimuli) estimates of speech rate fully capture the range of performance in bilingual digit span tasks. The level of inconsistency in speech rate estimation between studies has made the understanding of the relationship between speech rate and bilingual memory span and the role of the phonological loop difficult. In addition, the possibility that distinct estimates of speech rate index different processes in bilingual functioning cannot be discounted. It was, therefore, of some value to examine the power of three commonly used methods of estimating speech rate in predicting bilingual digit span as a means of scrutinising the relationship between speech rate and bilingual digit span proposed by working memory theory in closer detail.

In Experiment 2 the relationship between articulation time, and reading time for numeral and digit word stimuli and auditory digit span for two groups of Finnish schoolchildren in nine school grades (1-9) was compared. The subjects were grouped into two bilingual types that spoke either Swedish in the home and school (SS), or Finnish at home and Swedish at school (FS).

The main question under investigation was which of the speech rate estimates (articulation rate, digit word reading rate, or numeral reading rate) would best predict the relationship between the languages for the digit span task. Memory span was measured in the auditory modality, therefore, as Hitch et al. (1989) have suggested, articulation rate is the more appropriate index of the rate of subvocal rehearsal. If the bilingual digit span effect is exclusively mediated by phonological loop functioning and differences in digit articulation duration between the languages, articulation rate, the speech rate estimate least influenced by factors related to familiarity with the visual stimuli, should be the most reliable predictor of the relationship between Swedish and Finnish digit span.

3.2: Second-Language Schooling and Digit Span Development

The present design allowed questions related to the development of bilingual digit span to be addressed. The results of Experiment 1 indicated that Swedish mother tongue-Finnish schooled, and Finnish mother tongue-Swedish schooled bilingual university students obtained equivalent digit spans and numeral reading rates in both languages. These findings, of course, applied to bilinguals who had successfully negotiated schooling in a second language and were embarked upon undergraduate careers. Mägiste (1979), on the other hand, traced the developmental change in a variety of language processing tasks for German mother tongue children attending school in Sweden. She found that response latencies were faster in German than Swedish for children who had resided in Sweden for up to 5.5 years. After this length of residence

Mägiste (1979) observed a point of language balance and shift and thereafter performance was faster in Swedish than German. When performance in Swedish by this group was compared to that of Swedish monolinguals, the German-Swedish bilinguals did not attain a comparable level of native speaker fluency even after 17 years of residence in the host country. Mägiste (1979), thus, suggested that bilinguals are unlikely to attain native speaker fluency in the second language.

It was of some interest, therefore, to investigate the consequences of schooling in a second language on digit span performance. On the basis of Mägiste's (1979) findings, it seemed plausible that FS bilinguals could be disadvantaged in terms of digit span capacity in the language of schooling relative to SS bilinguals. This would be a finding of some consequence as bilingual digit span and arithmetic proficiency are known to vary according to language (Chan, 1981; Ellis, 1992) and digit span is positively correlated with mathematical ability (Hoosain & Sallili, 1988). Further, by tracing the developmental trend in bilingual digit span across 9 school grades, it could be ascertained if a point of language balance and shift similar to that observed for linguistic information processing skills (Mägiste, 1979) could be extended to memory span performance.

To summarise, in this experiment the predictive power of three speech rate estimates in relation to bilingual digit span was compared in order to interpret the findings of previous bilingual studies more conclusively. If bilingual auditory digit span is mediated exclusively by variation in digit name word length, articulation rate, the measure least affected by factors related to the recognition of printed stimuli, should be the most reliable predictor of memory span. In addition, comparing performance by native and non-native speakers of the language of schooling allowed the consequences of receiving schooling in a second language in relation to memory span capacity for digits to be evaluated.

3.3: EXPERIMENT 2

3.3.1: Method

Subjects

The subjects were 204 schoolchildren (104 female and 100 male) ranging in age from 7 to 16 years (Grades 1 to 9) attending Swedish-medium schools in Turku, Finland. Approximately 600 children completed a questionnaire that established which language was used to communicate with each parent, siblings, caregivers, and friends. Teachers were consulted and confirmed the reliability of responses to the questionnaire. These data were then used to select two groups from each cohort. One group consisted of children who had the same mother tongue and language of schooling (SS). The other comprised children who spoke Finnish in the home and received schooling in Swedish (FS).

In each cohort FS bilinguals were in a minority and these subjects were identified first. An equivalent number of subjects, matched for sex, was then selected at random from the corresponding sample of SS bilinguals. This procedure resulted in a sample consisting of 24 subjects at each grade level, except for grades 1, 2, and 4 which consisted of 20 subjects at each grade level, being selected for testing.

Materials

For the measurement of reading time, four lists of 100 random digits (1-9) were constructed with the restriction that each digit occurred with the same frequency in each list. The consecutive repetition of items was avoided as were ascending and descending sequences of more than two items (e.g., 6,7,8 or 5,4,3). Two lists were printed in Arabic numerals and the two remaining lists comprised either Swedish or Finnish digit words. Each list was printed in 10 rows of ten items.

For the measurement of articulation time, a set of three digit triads was constructed at random using the digits from 1 - 9 without replacement. This triad set was varied systematically to make a total of nine sets of three triad sequences.

For the measurement of digit span in each language, two sets of random digits (1 - 9) were prepared. Each set commenced with two, 1 digit sequences, followed by two, 2-digit sequences, and so on until a maximum of two, 12 digit sequences. Items appearing contiguously, ascending and descending sequences were avoided.

Procedure

Subjects were tested individually by a fluent Finnish-Swedish bilingual and the language in which the instructions were given was counterbalanced. Subjects were instructed to use standard digit names for both languages throughout the test session. First, measures of reading time for 100 numerals and digit words in Finnish and Swedish were taken. The subjects were instructed to read the digit lists as quickly as possible pronouncing each digit individually and audibly. The Experimenter indicated when reading should commence and measured the time taken by stopwatch. Language of practice, and list order were counterbalanced. Prior to the test block subjects practised reading a list of 50 numerals and the language of practice was counterbalanced.

Next, measures of articulation time in Finnish and Swedish blocked by language were taken. The subjects were instructed to memorise the digit triad presented by the Experimenter and to articulate the sequence as fast as possible when instructed to do so. After presenting the digit triad in the target language, the Experimenter indicated with a nod that articulation should commence, counted ten triad repetitions, and measured the time taken by stopwatch. Three articulation measures were taken for each language with triad and language counterbalanced by a Latin square.

Finally, measures of digit span in Finnish and Swedish were taken. The digit sequences were blocked by language and read aloud by the Experimenter at the rate of one digit per second. After reading the digit sequence, the Experimenter indicated with a nod that recall should commence. Testing continued until two consecutive errors at the same sequence length were made. Digit span was operationalised as the length of last correctly recalled sequence. If both responses at the last sequence length were correct, a score of 0.5 was added. The digit sequences and the language of presentation were counterbalanced.

The time spent on each task varied across grade. The younger children took longer than the older children in the articulation rate tasks, whereas for the digit span task the reverse was the case. The average length of a test session was approximately 15 min and therefore the effects of fatigue or decrease in attention were unlikely to have been of major consequence.

3.3.2: Results

Numeral Reading

The numeral reading data were converted into measures of time per digit (msec/digit). A Bartlett's Test for homogeneity of variance revealed that the variances were not homogenous ($\chi^2 = 11.76$, $p < .01$). The data were therefore subjected to a square root transformation and a three-way analysis of variance performed in which grade (1 to 9), and bilingual type (SS or FS) were between-subjects factors and language (Finnish or Swedish) was a within-subjects factor and are summarised by bilingual type in Figures 3.1 and 3.2.

This revealed a significant effect of grade (F (8,186) = 50.71, $p < .0001$), bilingual type (F (1,186) = 10.482, $p < .01$, means SS = 923, FS 764), and language (F (1,186) = 131.21, $p < .0001$, means Swedish = 695 msec/digit, Finnish = 992 msec/digit). Interactions between grade and language (F (8,186) = 1.99, $p < .05$) and bilingual type and language (F (8,186) = 63.54, $p < .0001$) were reliable and were qualified by the presence of a reliable second order interaction between the factors (F (8,186) = 3.29, $p < .01$).

Analysis of the three-way interaction by simple main effects revealed that at each grade level SS bilinguals consistently read numerals faster in Swedish than Finnish (all F (1,186) > 7, $p < .01$), whereas no differences between the languages were present for each grade level of the FS bilingual type (all F (1,186) < 2.29, $p >$

.10) and hence the interaction term. Performance in Finnish between the groups differed for grades 1-3 with a shorter numeral reading time for FS than SS, whereas no differences for Swedish were present.

Inspection of the means (Figure 3.1) suggested that, as a group, FS were systematically slower in Finnish than Swedish although the overall magnitude of the effect was greater for SS than FS (531 and 64 msec/digit respectively). It seemed probable that the presence of a second-order interaction was due to variation in the magnitude of language difference between the groups rather than the absence of a language effect for FS.

In order to examine the possibility that the low number of subjects at each grade level did not provide the necessary power to detect a language difference for FS within the second order interaction, the data were re-examined separately according to bilingual type. The FS data were subjected to a two-way analysis of variance in which grade was a between-subjects factor and language was a within-subjects factor. This revealed main effects of grade (F (8,93) = 27.83, $p < .0001$), and language (F (1,93) = 42.07, $p < .0001$) with a shorter reading time for Swedish than Finnish (732 and 796 msec/digit respectively), and no interaction between the factors (F (8,93) = 1.50).

A corresponding analysis of the SS data revealed main effects of grade (F (8,93) = 24.45, $p < .0001$), language (F (1,93) = 101.67, $p < .0001$), and an interaction between the factors (F (8,93) = 2.72, $p < .01$). Analysis of the interaction by simple main effects indicated a shorter reading time for Swedish than Finnish for all grades (all comparisons $p < .05$). The magnitude of the language effect was larger for the first three grades ($F > 24$) than the remaining six ($3.95 < F < 7.36$) and hence the interaction term.

To summarise, the results indicated a consistently shorter numeral reading time for Swedish than Finnish for SS, whereas FS had an equivalent reading time between the languages. The magnitude of the language difference was greater for SS than FS and this variation between the groups rather than an absence of a language effect for FS was responsible for the three-way interaction.

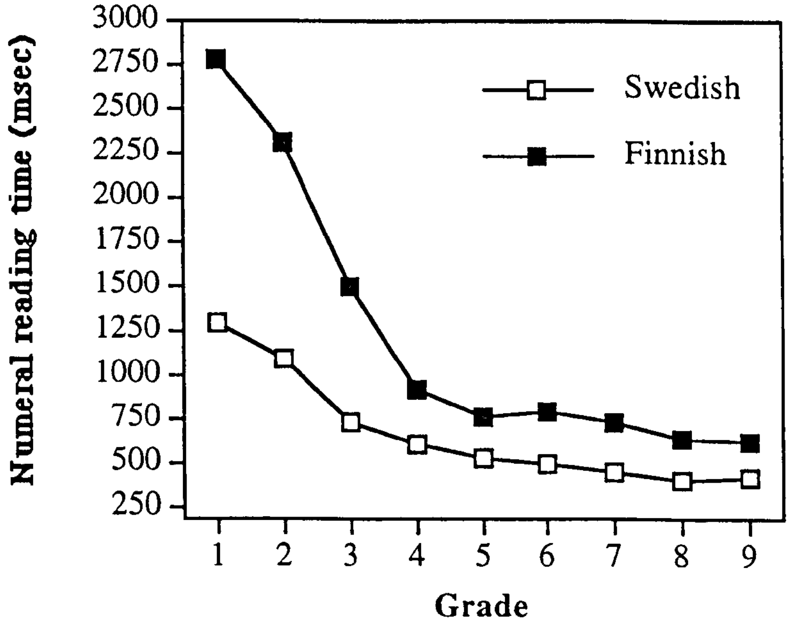

Figure 3.1: Mean numeral reading time (msec/item) in Swedish and Finnish for SS bilinguals.

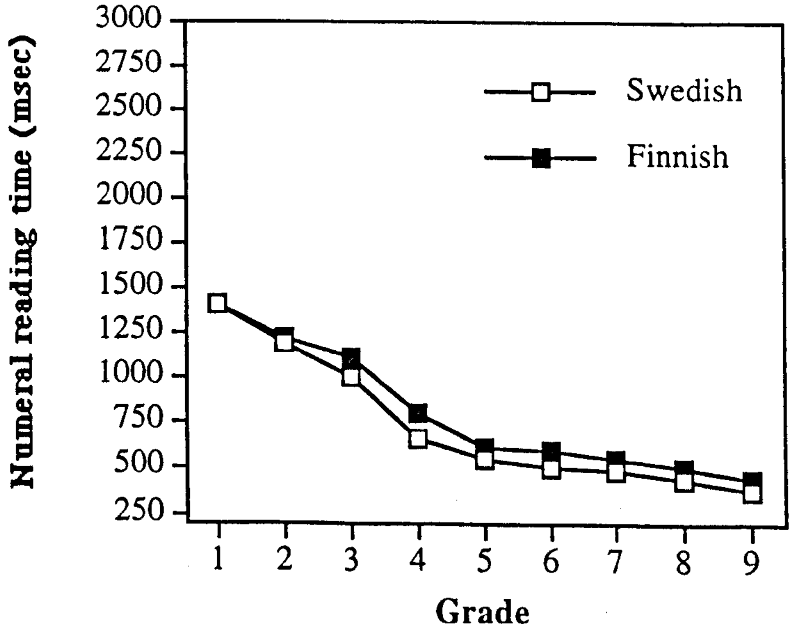

Figure 3.2: Mean numeral reading time (msec/item) in Swedish and Finnish for FS bilinguals.

Digit Word Reading

The digit word reading data were converted into measures of time per digit and are summarised by bilingual type in Figures 3.3 and 3.4. A Bartlett's Test for homogeneity of variance revealed that the variances were not homogenous (χ^2 = 112.46, $p < .01$). The data were, therefore, subjected to a square root transformation and a three-way analysis of variance performed in which grade (1 to 9), and bilingual type (SS or FS) were between-subjects factors and language (Finnish or Swedish) was a within-subjects factor. This revealed a reliable effect of grade (F (8,186) = 40.40, $p < .0001$) and language (F (1,186) = 224.38, $p < .0001$) with a shorter reading time in Swedish than Finnish (means = 646 msec/digit and 866 msec/digit respectively). The interactions between grade and language (F (8,186) = 15.36, $p < .0001$), and bilingual type and language (F (1,186) = 4.73, $p < .05$) were reliable, but the three-way interaction was not (F (8,186) = 0.74).

Analysis of the interaction between grade and language by simple main effects indicated a difference between Swedish and Finnish at all the grade levels with performance in Swedish consistently faster than Finnish (all comparisons $p < .05$). The magnitude of the language difference varied between grades with the effect being larger for the first three grades ($F > 30$) than the remaining six ($1 < F < 10$) hence the interaction term. Further analysis of the interaction by simple main effects indicated differences in reading rate in both Swedish (F (8,372) = 25.67, $p < .0001$) and Finnish (F (8,372) = 45.92, $p < .0001$) as a function of grade.

Analysis of the interaction between bilingual type and language revealed that both bilingual types had a shorter digit words reading time in Swedish than Finnish. For SS (F (1,186) = 137.29, $p < .0001$) the means were 654 msec/digit and 898 msec/digit respectively, and for FS (F (1,186) = 75.53, $p < .0001$) the means were 638 msec/digit and 833 msec/digit respectively. The magnitude of the language effect was larger for SS (244 msec) than FS (195 msec) and hence the interaction term. The between-group differences for Swedish and Finnish were not reliable.

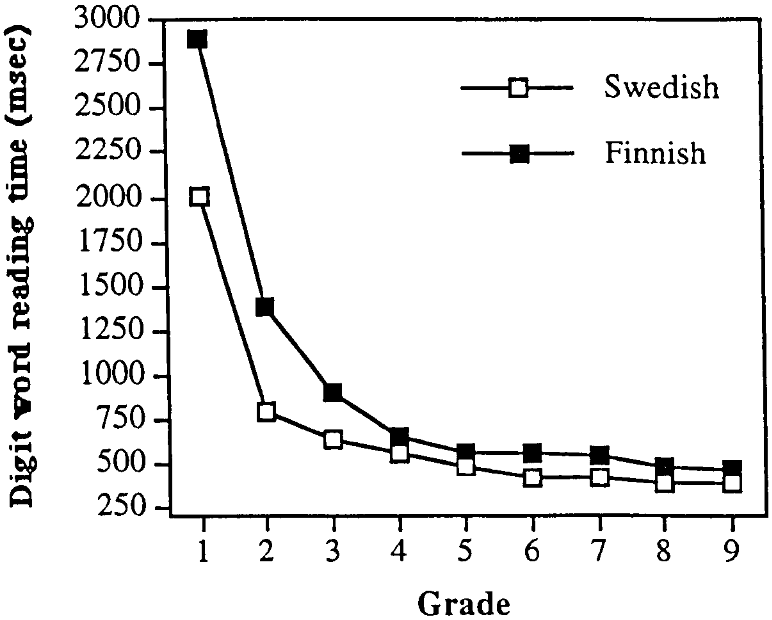

Figure 3.3: Mean digit word reading time (msec/item) in Swedish and Finnish for SS bilinguals.

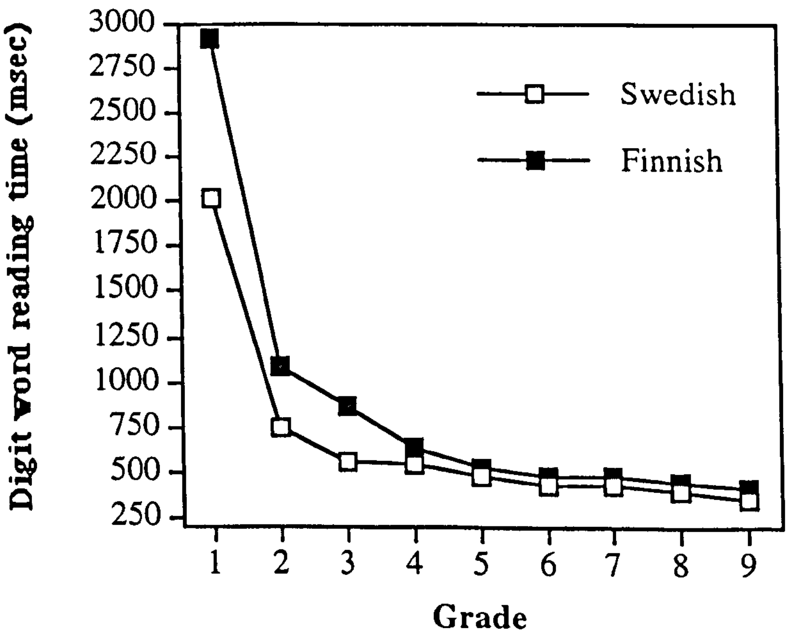

Figure 3.4: Mean digit word reading time (msec/item) in Swedish and Finnish for FS bilinguals.

The data were analysed separately according to bilingual type in order to examine if the statistical suggestion of the effects observed in the overall analysis may have been a result of a low statistical power in the design. A two-way analysis of variance was constructed for the FS data in which grade was a between-subjects factor and language was a within-subjects factor. This revealed main effects of grade (F (8,93) = 15.48, $p < .0001$), language (F (1,93) = 97.90, $p < .0001$) with a shorter reading time for Swedish than Finnish (638 and 833 msec/digit respectively), and an interaction between the factors (F (8,93) = 9.06, $p < .0001$). Analysis of the two-way interaction by simple main effects indicated that the language difference at the first three grade levels was reliable ($F > 35$), whereas for the remaining six grades no language difference was present and hence the interaction term.

A corresponding analysis for the SS data revealed main effects of grade (F (8,93) = 27.87, $p < .0001$), language (F (1,93) = 126.55, $p < .0001$) with a shorter reading time for Swedish than Finnish (654 and 898 msec/digit respectively), and an interaction between the factors (F (8,93) = 7.32, $p < .0001$). Analysis of the interaction by simple main effects indicated a shorter reading time for Swedish than Finnish for all grades (all comparisons $p < .05$) with the exception of grades 4, 5, 9 where the differences were marginal ($p < 10$). The magnitude of the language effect was larger for the first three grades ($F > 20$) than the remaining six ($2 < F < 9$) and hence the interaction term.

To summarise, the results of the separate analysis by bilingual type indicated a shorter digit word reading time for Swedish than Finnish for SS. The results for the FS group indicated a shorter digit word reading time for Swedish for the first three grade levels (1-3) and no difference for the remaining grades (4-9).

Articulation Time

The data from the articulation task were averaged and converted into measures of time per digit and are summarised by bilingual type in Figures 3.5 and 3.6. These data were subjected to a three-way analysis of variance in which grade (1-9) and bilingual type (SS or FS) were between-subjects factors and language (Finnish or Swedish) was a within-subjects factor. This showed a significant effect of grade (F (8,186) = 23.61, $p < .0001$), bilingual type (F (1,186) = 13.44, $p < .001$, means SS = 410 msec/digit, FS = 374 msec/digit), and language (F (1,186) = 636.06, $p < .0001$, means Finnish = 449 msec/digit, Swedish = 335 msec/digit). A significant interaction between the bilingual type and language factors (F (1,186) = 148.1, $p < .0001$) was qualified by a reliable second order interaction between the factors (F (8,186) = 2.53, $p < .05$).

Analysis of the three-way interaction by simple main effects indicated a shorter articulation time in Swedish than Finnish for both bilingual types and at all grade levels (all F (1,186) > 4.6, $p < .01$) with the exception of the FS bilingual type at the grade 1 level where no difference in articulation time between Swedish and Finnish was present. Articulation time varied as a function of grade for each bilingual type in both Finnish and Swedish (all F (8.186) > 5, $p < .0001$). Overall the magnitude of the language effect was greater for SS than FS (167 vs. 59 msec/digit) and hence the interaction term.

Comparison of Swedish articulation time between bilingual types indicated no differences were present at any grade level. The results for Finnish were less consistent and differences were revealed for grades 1 ($p < .001$) , 3 ($p < .01$), 6 ($p < .05$), 7 ($p < .05$), and 8 ($p < .05$) with FS obtaining a shorter articulation time than the SS bilingual type. In order to ensure an equivalence in the statistical treatment of the data across the analyses of the four tasks the articulation rate and memory span data were further subjected to separate analyses by bilingual type. The results of these analyses, however, were consistent with those of the overall analyses of variance and are not reported for economy of presentation.

To summarise, articulation time was consistently shorter in Swedish than Finnish for both bilingual types with the exception of the grade 1 cohort of the FS group where no language difference was present.

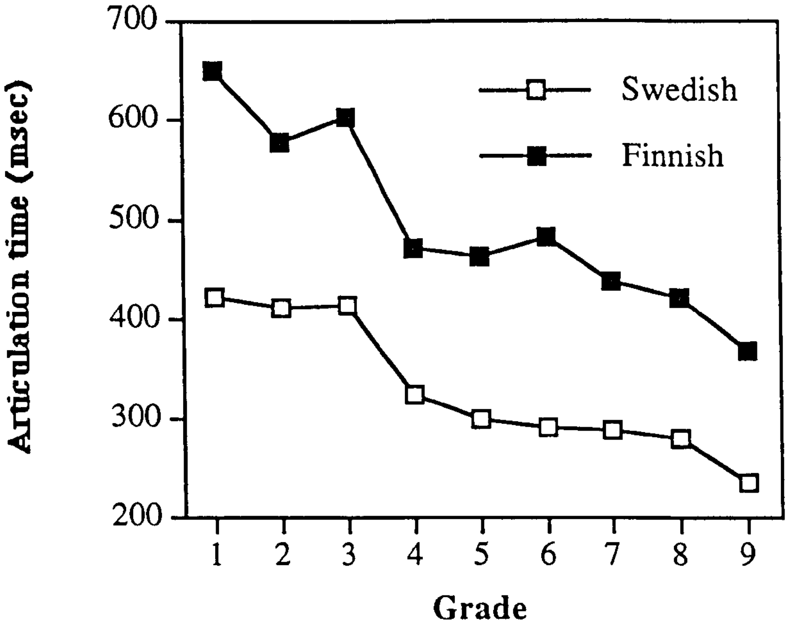

Figure 3.5: Mean articulation time (msec/item) in Swedish and Finnish for SS bilinguals.

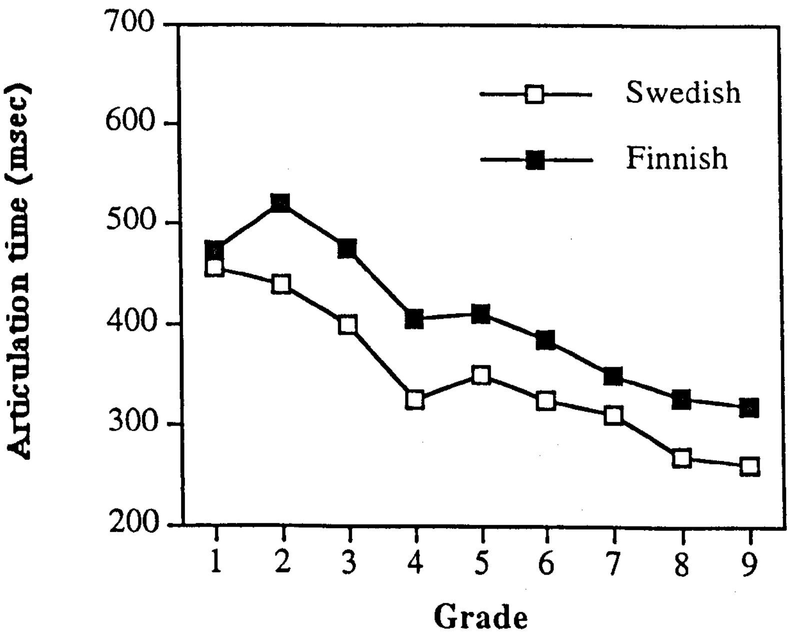

Figure 3.6: Mean articulation time (msec/item) in Swedish and Finnish for FS bilinguals.

The results of the speech rate tasks may be summarised as follows. Both SS and FS obtained shorter articulation time and numeral reading time in Swedish than Finnish (except for FS grade 1): the magnitude of the language effect being greater for SS than FS. Both of these speech time estimates, thus, predicted a larger digit span in Swedish for SS and FS. Digit word reading time varied between bilingual types. In this case the first three grade levels (1-3) for both SS and FS read digit words faster in Swedish than Finnish. Grades 4 - 9 in the FS group read digit words at equivalent rates in Swedish and Finnish, whereas the same grades in the SS group read digit words faster in Swedish.

With regard to the between-group comparisons the speech time estimates were equivalent for Swedish. For Finnish no difference was present between bilingual types for digit word reading, whereas FS had a shorter articulation time than SS for 5 of the grade levels and a shorter numeral reading time for the first 3 grade levels. As far as speech time was concerned, then, the present findings indicated that receiving schooling in a second language did not disadvantage FS performance in Swedish compared to native speakers of the same language.

Auditory Digit Span

The digit span data were subjected to a three-way analysis of variance in which grade and bilingual type (SS or FS) were between-subjects factors and language was a within-subjects factor and are summarised by bilingual type in Figures 3.7 and 3.8. This indicated a reliable effect of grade (F (8,186) = 11.878, $p < .0001$) and language (F (1,186) = 65.73, $p < .0001$) with digit span larger in Swedish than Finnish (means = 5.67 and 5.14 respectively). The only reliable two-way interaction was that between the bilingual type and language factors (F (1,186) = 37.59, $p < .0001$). The three-way interaction was not reliable (F (8, 186) = 1.1)

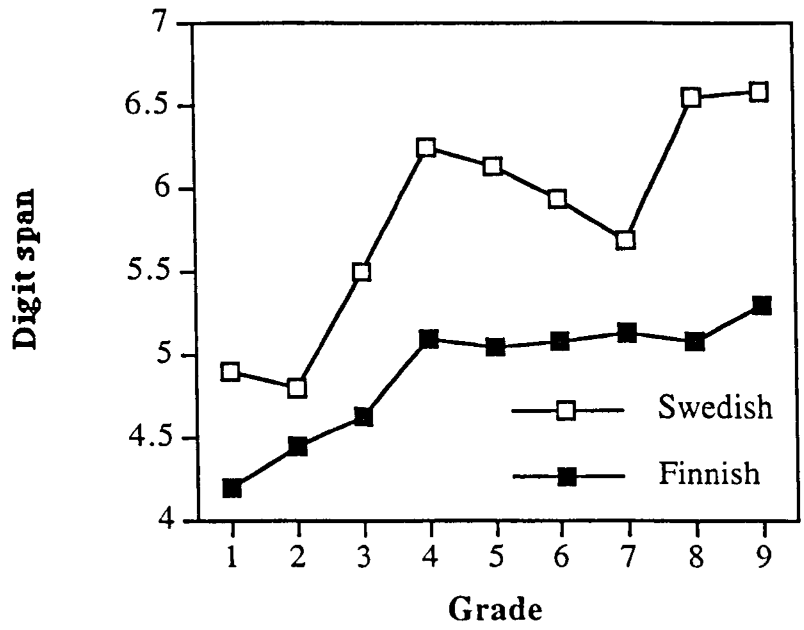

Figure 3.7: Mean auditory digit span in Swedish and Finnish for SS bilinguals.

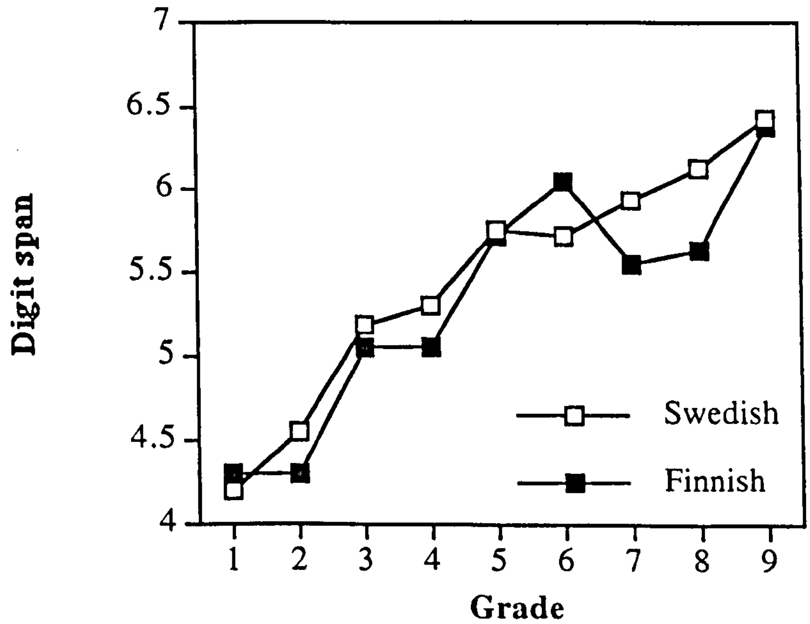

Figure 3.8 Mean auditory digit span in Swedish and Finnish for FS bilinguals.

Analysis of the interaction between bilingual type and language by simple main effects indicated that SS obtained larger digit spans in Swedish than Finnish (F (1,186) = 104.57, $p < .0001$, means = 5.84 and 4.91 respectively). No difference between Swedish and Finnish digit span was present for the FS bilingual type and hence the interaction term. Language differences between the bilingual types were present for Swedish (F (1,372) = 6.45, $p < .05$) and Finnish (F (1,372) = 12.85, $p < .001$) digit span. SS bilinguals obtained larger digit spans in Swedish than FS (means = 5.84 and 5.51 respectively), whereas FS obtained larger digit spans in Finnish than SS (means = 5.38 and 4.91 respectively).

To summarise, the results of the digit span task indicated that SS bilinguals obtained larger digit spans in Swedish, as predicted by the three speech rate estimates. FS bilinguals, however, obtained equivalent digit spans in both languages despite articulating and reading numerals faster in Swedish. Thus for FS the digit word reading task was the only speech time measure that predicted memory span performance, and then only for grades 4 to 9 .

Regarding between-group performance in Swedish, SS bilinguals obtained larger digit spans in Swedish than FS. This finding indicated that, despite equivalent speech rate performance in Swedish between the groups, FS bilinguals were disadvantaged in memory span capacity for Swedish digits compared to native speakers of the language of schooling (SS).

Correlational Analyses

A series of Pearson correlational analyses was performed on the data in order to examine the relationship between each speech time estimate and digit span for Swedish and Finnish and are summarised in Table 3.1. The results showed that the three estimates of speech time were reliably correlated with digit span for each language for both bilingual types.

In order to examine the relationship between the correlations, tests of the significance of the difference between correlations (Cohen & Cohen, 1983) were conducted and are summarised in Table 3.2. The results indicated that for SS bilinguals no differences were present between the correlations for each speech time measure and Finnish digit span. For Swedish digit span, numeral reading time correlated more highly than digit word reading time and no other differences between the correlations were present. For FS numeral reading time correlated more highly with Finnish digit span than digit word reading time, whereas both articulation time and numeral reading time were more highly correlated with Swedish digit span than digit word time.

Table 3.1: Correlations between speech time measures and auditory digit span in Swedish and Finnish.

	SS bilinguals		FS bilinguals	
Speech time	Swedish	Finnish	Swedish	Finnish
Articulation	-.34	-.34	-.47	-.46
Numerals	-.38	-.25	-.47	-.50
Digit words	-.27	-.34	-.34	-.37

All correlations significant to $p < .01$

An identical pattern of results was, thus, present in the first language for both SS and FS bilinguals with a higher correlation for numeral reading time compared to digit word reading time. The results varied for the second language with SS bilinguals showing no difference between the three speech time estimates and Finnish digit span, whereas for FS digit word reading rate was correlated to a lower degree with Swedish digit span than both articulation time and numeral reading time. The results also indicated that articulation time and numeral reading time were correlated equivalently with digit span in each language for both bilingual types.

Although the comparison between the correlations did not demonstrate conclusively that the speech estimates indexed different processes the results indicated that digit word reading rate correlated to a lower degree than numeral reading time with digit span in three out of four possible cases. Paradoxically, it was the digit word reading task that best predicted memory span performance overall.

Table 3.2: Significance of the difference between correlations for speech time measures and digit span in Swedish and Finnish for two bilingual types.

	SS bilinguals				FS bilinguals			
	Swedish		Finnish		Swedish		Finnish	
Speech time	t	p	t	p	t	p	t	p
Articulation vs. numeral	0.00	n.s.	1.35	n.s.	0.00	n.s.	0.78	n.s.
Articulation vs. Digit word	1.06	n.s.	0.00	n.s.	2.24	< .01	1.3	n.s.
Numeral vs. Digit word	2.26	< .01	1.23	n.s.	3.90	< .01	3.14	< .01

3.3.3: Discussion

The motivation for the present study was twofold. First, it tested which of three estimates of speech time (numeral reading, digit word reading, or digit articulation) best predicted the relationship between the languages on an auditory memory span task. Second, it examined whether schoolchildren receiving schooling in a second language were disadvantaged in terms of memory span performance for digits relative to peers who were native speakers of the language of instruction.

It was reasonable to assume that articulation time was the most accurate index of the speed of subvocal rehearsal as this measure is unaffected by factors related to the recognition of visual stimuli (Hitch et al., 1989) and memory span was measured in the auditory modality. The present findings indicated that SS bilinguals consistently articulated digits faster in their dominant language (Swedish) and that digit span was larger in Swedish than Finnish. Although FS also articulated digits faster in Swedish than Finnish in this case, however, articulation time did not predict the equivalent memory span between the languages. Now, if, as proposed by working memory theory, memory span is mediated by the rate of subvocal rehearsal, articulation time should have predicted the digit span relationship between Swedish and Finnish for both bilingual types.

The answer to the variation in the predictive power of articulation rate could lie in differences in the level of relative bilingual fluency between SS and FS. To explain, between-group comparison of articulation rate revealed that both bilingual types performed equivalently for Swedish, whereas over half of the SS group obtained a longer articulation time in Finnish compared to FS. These findings suggested that FS were the more balanced bilinguals and that the majority of SS did not perform at a level comparable to native speakers of Finnish.

For SS, then, the superior performance in speech time and memory span for Swedish by SS bilinguals was mediated by factors related to a higher level of fluency in Swedish relative to Finnish. Therefore, verbal fluency and the strength of long-term representations were confounded making it impossible to extricate the relative contributions of these factors. For FS, however, the possibility that a low level of verbal fluency in the second language may have affected performance could be discounted as articulation rate was equivalent to that of native speakers. Instead, the present findings suggested that the pattern of memory span involved factors other than phonological loop functioning as the only estimate of speech time that predicted performance on the memory span task for FS was one that involved the recognition of printed stimuli.

For the speech time estimates involving reading, SS obtained shorter numeral and digit word reading times in their dominant language (Swedish). The results for the FS group showed that numerals were read faster in Swedish as were digit words for the first three grade levels, whereas for the older grade levels (4-9) no difference was present for digit words.

The shorter numeral reading time in Swedish than Finnish by FS was likely to have been a result of receiving schooling in the same language as Experiment 1 identified the language of schooling as an influential determinant of bilingual digit span for numeral stimuli. This was, plausibly, due to the massive levels of practice in counting and computation associated especially with elementary education. Having been schooled in Swedish, FS bilinguals were likely to be more practised in processing numeral stimuli in Swedish and this may have been the critical variable affecting performance. Numeral reading performance by FS may, therefore, have been disrupted by Stroop-type interference from the more familiar language for numerals and this could explain why this estimate of speech rate did not predict auditory memory span as familiarity with the printed numeral stimuli was not a factor of any consequence for the latter task.

Digit words, on the other hand, offer more direct assistance through separate language-specific representations and lexical support and are unlikely to activate output in the dominant language as they engage separate decoding and encoding processes from the outset. Nevertheless, digit word reading performance was likely to have been affected by the level of familiarity with the printed stimuli. It seemed natural to suggest that bilingual children receiving schooling in a second language acquire reading skills at a faster rate in the language of the school compared to that of the home. For the present FS group, this resulted in longer reading time for Finnish digit words relative to Swedish ones in the first three grades. By grade 4, however, FS bilinguals read digit words at equivalent rates between the languages despite articulating and reading numerals faster in Swedish.

The present study was incapable of identifying the factors that mediated equivalent digit word reading rates between the languages for the older FS grades nor could it be established precisely why articulation rate did not predict the relationship between the languages in the memory span task for these bilinguals. It was posited that the observed equivalence in digit span for the FS group may have been mediated by an interplay between the strength of long-term memory representations and subvocal rehearsal speed in which stronger representations in Swedish attenuated by a shorter articulation time in Finnish. To explain, using the number of syllables as an approximate index of word length, the articulatory duration of digits was likely to be shorter in Swedish than Finnish (1.22 and 2.33 syllables per digit is respectively, Appendix 2.1). Although this hypothesised word length advantage occasioned a shorter articulation time for Swedish, it was not sufficient to attenuate the stronger long-term representations for Finnish digits. The combination of these two factors may have resulted in the observed equivalence between the languages in the memory span task.

If this explanation was correct, it suggested that word length (as estimated by articulation time) plays a role, though not an exclusive one, in mediating bilingual memory span. Instead a word length advantage in the bilingual's second language may be viewed as a factor that exerts an attenuating effect on the natural bias in the strength of long-term representations in favour in the mother tongue. In the present study this resulted in equivalent in memory spans between the languages. There may be circumstances, however, under which specific relationships between word length and long-term representations do occasion a larger memory span in the mother tongue relative to the language of schooling (Elliot, 1992), although the precise parameters that determine such relationships have yet to be specified. The contribution of long term representations in mediating bilingual memory span performance was examined in more detail in the studies presented in Chapter 4.

A second motivation for the present study was to examine differences between native and non-native speakers of the language of schooling and the digit span relationship between the languages development of digit span for bilinguals receiving schooling in a language other than the mother tongue. In terms of between-language digit span, performance by FS was remarkably stable and an equivalence between Finnish and Swedish was present at all grade levels. Thus, for the present FS bilinguals there was no evidence of a shift toward superior performance in the language of schooling as may have been predicted on the basis of findings of Mägiste (1979). The present results further indicated that when performance was specified in Swedish, SS and FS performed equivalently on the three speech tasks. However, this pattern of performance was not present in the memory span task were SS obtained larger spans than FS in Swedish: a finding that strengthened the view that memory span was not exclusively mediated by speech rate. Given the positive correlation between mathematical ability and memory capacity for digits (Hoosain & Sallili, 1988) the present findings suggested that the present FS bilinguals, non-native speakers of the language of schooling, may be disadvantaged in cognitive processing involving numbers compared to their native Swedish-speaking peers: a notion worthy of further investigation.

In short, the findings of Experiment 2 indicated that the difference in digit span between the languages of the bilingual was not exclusively due to variation in the articulatory duration of digit names and the rate of subvocal rehearsal. Instead, it seemed likely that factors associated with retrieval from long-term memory and the strength of long-term representations made an independent contribution to memory span: a notion consistent with the findings of Hulme et al. (1991, 1995). This notion was investigated further in the following study.

Chapter 4

Long-Term Memory Representations and Bilingual Memory Span

The finding that articulatory suppression eliminated the language difference in digit span for the constant bilingual types (Experiment 1) supported the view that the bilingual word length effect is mediated by phonological loop functioning (Chincotta & Hoosain, 1995). The finding that digit word reading time was a better predictor of auditory digit span than articulation time (Experiment 2), however, indicated that performance on the memory span task involved factors other than subvocal rehearsal. This was concluded on the basis that articulation time should have been a better predictor of covert speech rate than a measure that involved the visual recognition of the stimuli such as digit word reading (Hitch et al., 1989).

In this Chapter, two experiments are reported which examined the view whether the equivalence in numeral span (Experiment 1) and auditory digit span (Experiment 2) observed for the FS bilingual type was moderated by an interplay between the strength of long-term memory representations and speech rate. That is, could the stronger long-term representations for Swedish digits (as a consequence of schooling in that language) have been attenuated by a faster speech rate for Finnish digits (as a consequence of greater verbal fluency in the mother-tongue?

4.1: Long-term Memory Contributions to Short-term Memory

In its strongest form, working memory theory posits that memory span is mediated by two factors: the rate of subvocal rehearsal and the capacity of the phonological loop. The most compelling evidence against this simple view of working memory has been provided by Hulme and colleagues (Hulme, Maughan, & Brown, 1991; Roodenrys, Hulme, & Brown, 1993; Hulme, Roodenrys, Brown, & Mercer, 1995; Brown & Hulme, 1995). These studies have demonstrated that factors independent of speech rate are related to memory span. Hulme et al., (1991), for example, found that memory span was greater for words than non words even when items were matched for articulation duration. Under these circumstances the memory span difference between words and non words could not be attributed to variation in word length or the rate of subvocal rehearsal. Instead, a larger memory span for words was interpreted as resulting from a distinct contribution from long-term memory as non words were unlikely to have long-term memory representations.

More recently Hulme et al. (1995) examined whether the difference in memory span between words and non words was based on phonological or semantic representations in long-term memory. Teaching subjects the pronunciations of non words increased memory span for them and the improvement was independent of a corresponding increase in speech rate. Hulme et al. (1995), thus, identified a crucial contribution of long-term phonological representations in reactivating fading traces in the phonological store.

As has already been discussed, studies of bilingual memory capacity have generally relied on the use of digit stimuli as a means of investigating the relationship between speech rate and memory span. In the Ellis and Hennelly (1980) study, for example, Welsh-English bilinguals read Arabic numerals faster in English than Welsh and an inverse relationship between auditory memory span and numeral reading rate was found. Other studies (da Costa Pinto, 1991; Chincotta & Hoosain, 1995) have reported that numeral reading rate is a reliable predictor of bilingual digit span: a view supported by the findings of Experiment 1. In Chapter 3, however, it was argued that the use of language-neutral numeral stimuli in speech rate estimation may be injudicious given the possibility of Stroop-like interference from the dominant language for numerals (the language of schooling) when performance is measured in the less dominant language for numerals (A notion examined more directly in Chapter 5).

Support for this notion was obtained by the finding that FS bilinguals articulated digit names and read numeral stimuli faster in Swedish but obtained equivalent auditory digit spans between the languages (Experiment 2).

On the basis of these findings it was, thus, posited that there may be circumstances in which a predisposition for bilinguals to obtain larger digit spans in the language in which they are more fluent may be attenuated by a shorter word length in the less dominant language. Evidence for this view may be found in a study in which the relationship between articulation time independent of recognition and auditory digit span for four bilingual pairings was examined (Elliot, 1992). Here, correlations between the estimates of articulation time and digit span ranged from .37 to .45 for the collective sample. These group correlations, however, disguised the relationship for individual pairings where, for example, English-Mandarin bilinguals obtained equivalent digit spans in these languages despite a faster articulation rate for Mandarin. This finding is put into context when it is noted that a similar group of Mandarin-English bilinguals that also had a faster articulation time for Mandarin obtained a larger digit span in their dominant language.

These findings, then, were consistent with those of Experiment 2 in which a faster articulation time for Swedish by FS bilinguals did not predict an equivalence between the languages in the auditory digit span task. This pattern of findings occurred despite articulation time being regarded as a more adequate index of subvocal rehearsal rate than reading time (Hitch et al., 1989).

It would appear, thus, that there are circumstances in which a word length advantage in the bilingual's less dominant language may attenuate the natural advantage of the dominant language in digit span tasks (although the precise parameters that determine such relationships have yet to be specified).

Although studies of bilingual digit span have provided a useful means of testing predictions based on working memory theory the exclusive reliance on an over learned and restricted set of digit stimuli has constrained the implications that these findings may have in terms of furthering the understanding of bilingual information processing.

Additionally, the use of digit stimuli confounds familiarity and word length factors as it is not possible to control for differences in articulation duration for digit names between the languages. In Experiment 3, therefore, the relationship between speech rate and memory span was examined with stimuli other than digits (short and long words). This design allowed for a more informative manipulation of word length than has possible in studies involving digit stimuli.

Speech rate by FS bilinguals was compared to native speaker performance in Finnish and Swedish by including two control groups of asymmetric bilinguals that spoke the same language in the home and school, either Swedish (SS) or Finnish (FF). Although seldom used in studies of bilingual information processing the inclusion of such controls was an objective way of determining the relative level of fluency between Finish and Swedish for the FS bilinguals. It was reasoned that if FS speech rate was equivalent to speech rate performance by SS and FF in their respective dominant languages the possibility that memory span performance was affected by discrete levels of fluency between the languages would be minimised. The testing of subjects from two school grades (6 & 9) allowed an opportunity to examine whether the relationship between faster speech rate and larger memory span as a function of age present in monolinguals (e.g., Hulme and Muir, 1985; Henry and Millar, 1991) would be observed in bilinguals.

According to working memory theory, word length influences the rate of subvocal rehearsal which, in turn, determines a memory span that is limited by the temporal constraints of the phonological loop. The effects of word length have been shown to be robust for both word and non words (e.g., Hulme et al., 1991) therefore, it was predicted that a faster speech rate and larger memory span would be observed for short words relative to long words and that this pattern to be present in both languages across the three bilingual types.

The crucial question under investigation, however, was whether the relationship between the languages on the speech rate task would predict performance on the memory span task. The evidence from Experiments 1 and 2 suggested that the effects of speech rate in determining bilingual memory span may have been overplayed. In addition, Hulme and colleagues (1991, 1995) have demonstrated the influential contribution of factors other than speech rate on memory span. If, as posited by working memory theory, speech rate is the critical variable influencing bilingual memory span the between-language relationship for the speech rate tasks should be a reliable basis for predicting performance on the memory span task for all three bilingual types. If, on the other hand, factors such as long-term representations are influential determinants of memory span, speech rate should be a relatively poor predictor of the between-language relationship on the memory span task.

4.2: EXPERIMENT 3

4.2.1: Method

Subjects

The subjects were 72, Grade 6 and Grade 9 (approximately 12 and 15 years old respectively), Finnish-Swedish bilingual schoolchildren attending either a Swedish- or Finnish-language schools in Turku, Finland and were selected as follows. The Grade 6 and Grade 9 cohorts of the Swedish-medium school (approximately 50 and 100 children respectively) completed a questionnaire that established which language was used to communicate with each parent, siblings, caregivers, friends, and so on. Teachers were consulted on the selection of subjects and confirmed the reliability of the questionnaire responses. These data were used to select a group that spoke Finnish exclusively at home and received schooling in Swedish (FS). An equivalent number of subjects of that spoke Swedish both at home and school (SS) were then selected at random. A third group that spoke Finnish in both the home and school (FF) was selected at random from the Finnish-language schools with the criterion that these subjects had learned Swedish as a second language for approximately 3 or 6 years (Grade 6 and 9 respectively). Thus 12 subjects were selected for each bilingual type (FF, FS, & SS) at each Grade level (6 & 9).

Materials

Four word pools consisting of 8 short (1 syllable) and 8 long (3 syllable) nouns in both Finnish and Swedish (Appendix 2.2 and 2.3 respectively) were constructed using frequency counts for each language (Saukkonen, Haipus, Niemikorpi, & Sulkala, 1979; Allén, 1971 respectively). Analysis by t-test indicated no differences in frequency between the four word pools.

For the measurement of articulation time a set of 4 word pairs was constructed at random for each of the word pools with the restriction that each word occurred once in the set. These sets were then varied systematically to make a total of 8 sets for each pool. For the measurement of memory span a set of random word sequences was constructed for each word pool with the restriction that the same word should not occur contiguously. Each set commenced with two, 2 word sequences, followed by two, 3 word sequences, and so on until a maximum of two, 11 word sequences.

Procedure

The subjects were tested individually by a fluent bilingual and the language of instruction was counterbalanced. First subjects were asked to listen to and repeat each word in order to test the reproduction of the items. To measure articulation time, the experimenter read the word pairs and subjects were required to articulate this as fast as possible until instructed to stop. Subjects repeated the word pair until ten repetitions were counted by the experimenter and the time taken measured by stopwatch. The word pairs were blocked by language and word length and counterbalanced by a Latin square.

Next measures of memory span were taken. The word sequences were read aloud by the Experimenter at the rate of one word per second. When the sequence was completed the Experimenter indicated with a nod that recall should commence. Testing continued until two errors at the same sequence length were made. Memory span was operationalised as the length of the last correctly recalled sequence. If both sequences at the last length were correct a score of 0.5 was added. The sequences were blocked by language and word length and counterbalanced by a Latin square.

4.2.2: Results

Articulation Time

The articulation time data were averaged and converted into measures of time per digit and are summarised separately by bilingual type and grade in Figures 4.1 and 4.2. These data were subjected to a four-way analysis of variance in which grade (6 or 9) and bilingual type (FF, FS, or SS) were between-subjects factors and language (Finnish or Swedish) and word length (short or long) were within-subjects factors. This revealed reliable main effects of grade (F (1, 66) = 13.73, $p < .001$), with a shorter articulation time for grade 9 than 6 (means = 419.69 and 476.56 msec/item respectively), language (F (1, 66) = 312.19, $p < .0001$) with a shorter articulation time in Finnish than Swedish (means = 397.55 and 498.7 msec/item respectively), and word length (F (1, 66) = 866.69, $p < .0001$) with a shorter articulation time for short words than long words (355 and 541 msec/item respectively). The two-way interactions between grade and language (F (1, 66) = 14.76, $p < .001$), grade and word length (F (1, 66) = 28.99, $p < .001$), bilingual type and language (F (2, 66) = 100.01, $p < .001$), bilingual type and word length (F (2, 66) = 4.55, $p < .05$), language and word length (F (1, 66) = 153.73, $p < .0001$) were all reliable. These first order interactions, however, were qualified by the presence of reliable second order interactions between grade, language, and word length (F (2, 66) = 8.2, $p < .01$) and bilingual type, language, and word length (F (2, 66) = 21.67, $p < .0001$) were reliable. The four-way interaction was not reliable (F (2, 66) = 1.02).

Analysis of the three-way interaction between grade, language, and word length (F (2, 66) = 8.20, $p < .01$) by simple main effects indicated that short words were articulated faster than long words in both Finnish and Swedish and at both grade levels for (all $p < .0001$). Articulation time was shorter in Finnish than Swedish for both grades and for both short and long words (all $p < .01$). A difference between grade levels was observed for long words in both Finnish (F (1, 132) = 5.65, $p < .05$) and Swedish (F (1, 132) = 29.87, $p < .0001$) but not for short words. Thus, the shorter articulation times observed for the Grade 9 subjects was due to superior performance for long words in both languages.

Analysis of the three-way interaction between bilingual type, language and word length (F (2, 66) = 21.67, $p < .0001$) revealed that all the bilingual types articulated short words faster than long words at each language level (all $p < .0001$). Differences in articulation rate were present between bilingual type for long words both in Finnish (F (2, 132) = 8.53, $p < .001$) and Swedish (F (2, 132) = 19.62, $p < .0001$). A difference was also present for short words in Finnish (F (2, 132) = 4.06, $p < .05$) but not Swedish. Analysis by t-test revealed that FF and FS articulated Finnish short words (means = 306 and 316 msec/item respectively) and long words (means = 414 and 442 msec/item respectively) faster than SS (means short = 381, long = 526 msec/item); the differences reliable to the $p < .01$ level. No differences were present between FS and FF at either word length level in Finnish. In addition SS and FS articulated long words in Swedish (means = 569 and 571 msec/item respectively) faster than FF (724); the differences reliable at the $p < .001$ level. No difference was present between SS and FS.

Language differences were present for both short and long words for all bilingual types (all $p < .01$) with the exception of SS performance on short words where the difference was marginal (F (1, 66) = 3.24, $p < .08$). FF and FS articulated both short and long words faster in Finnish than Swedish, whereas SS articulated long words faster in Swedish and a marginally significant advantage for short words was present.

To summarise, the results of the articulation time task indicated that FS and FF bilinguals articulated items faster in Finnish than Swedish. Performance by SS varied as a function of word length with a shorter articulation time in Swedish for short words and a marginal advantage in Swedish for long words. The FS bilingual type articulated both long and short words at equivalent rates to dominant language performance by SS and FF. Grade 9 subjects articulated long words in both Finnish and Swedish faster than Grade 6 subjects, however short words were articulated at equivalent rates between the grades.

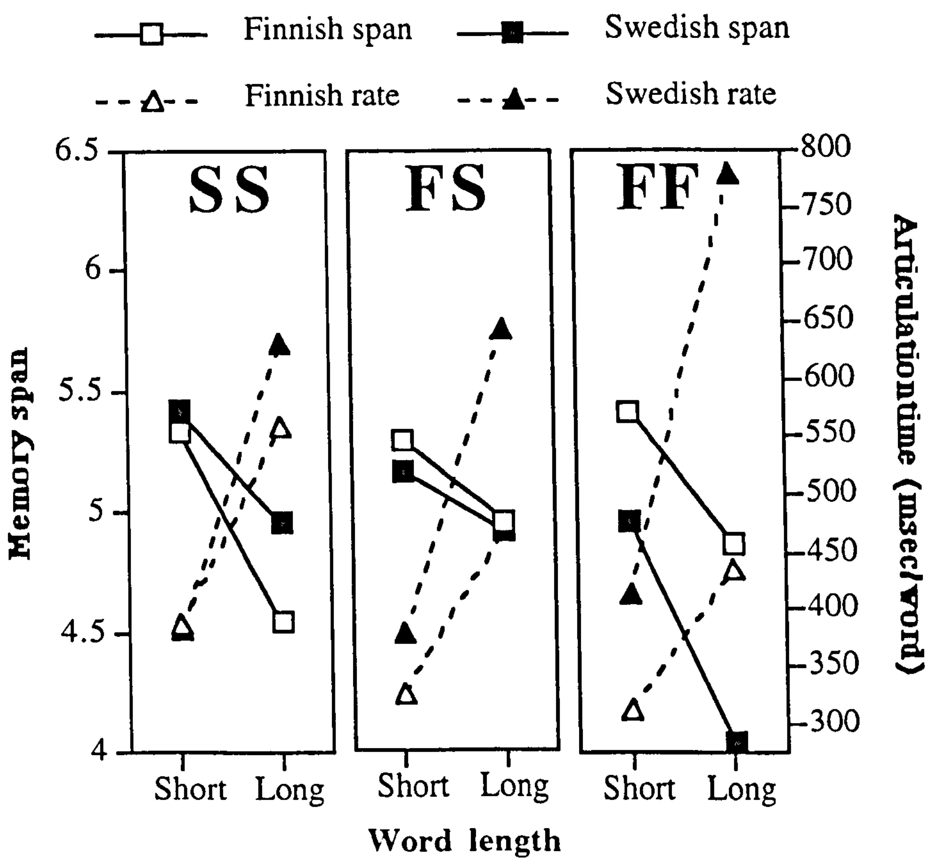

Figure 4.1: Mean articulation time (msec/word) and memory span for short and long words in Finnish and Swedish for three Grade 6 bilingual types

<u>Memory Span</u>

The memory span data were subjected to a corresponding four-way analysis of variance and are summarised by grade and bilingual type in Figures 4.1 and 4.2. This showed reliable main effects of language (F (1, 66) = 4.43, $p < .05$) with larger memory spans in Finnish than Swedish (means = 5.17 and 5.05 respectively), and word length (F (1, 66) = 42.87, $p < .0001$) with larger spans for short words than long words (means = 5.37 and 4.85 respectively). The interaction between bilingual type and language was reliable (F (, 66) = 33.09, $p < .0001$). None of the three-way ($F < 1.9$) or four-way ($F < 1$) interactions were reliable. No main or interaction effects were associated with the grade factor; a finding that indicated an equivalence in memory span between Grades 6 and 9.

Analysis of the interaction between bilingual type and language by simple main effects indicated a language difference in memory span for FF ($\underline{F}$ (1, 66) = 53.13, $\underline{p}$ < .0001, means Finnish = 5.28, Swedish = 4.53) and SS ($\underline{F}$ (1, 66) = 17.23, $\underline{p}$ < .001, means Finnish = 5.04, Swedish = 5.47). No language difference was present for FS bilinguals ($\underline{F}$ (1, 66) < 1, means Finnish = 5.2, Swedish = 5.15).

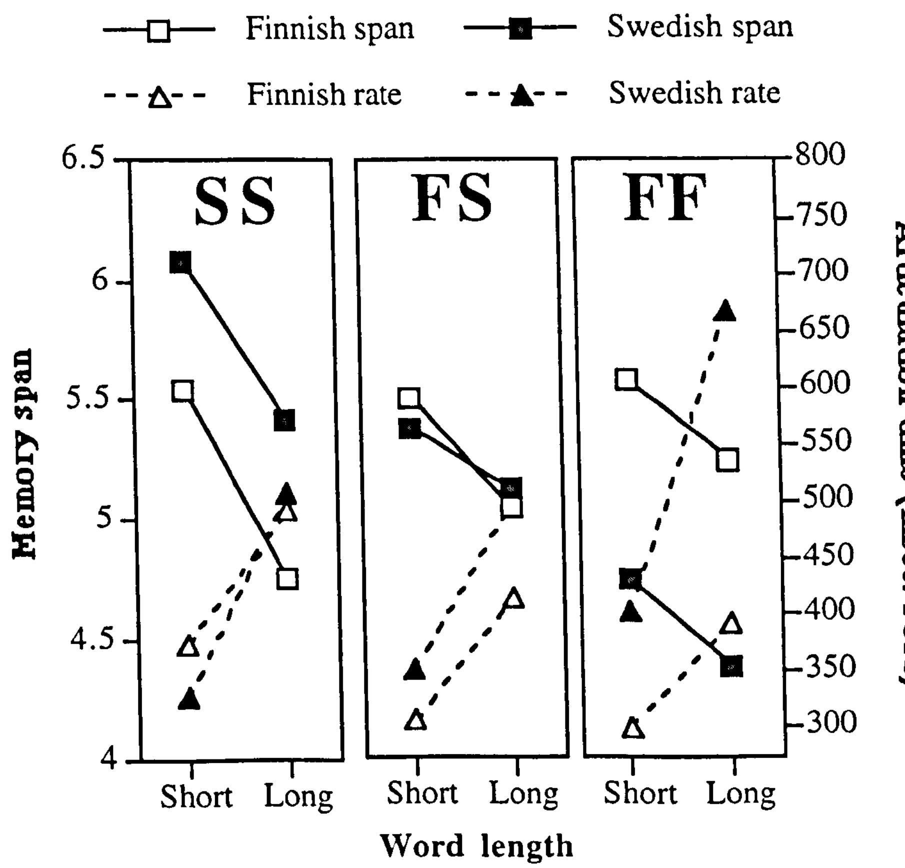

Figure 4.2: Mean articulation time (msec/word) and memory span for short and long words in Finnish and Swedish for three Grade 9 bilingual types.

Finnish memory span was equivalent between bilingual types ($\underline{F}$ < 1), whereas a difference was present for Swedish memory span across bilingual type ($\underline{F}$ (2, 132) = 10.80, $\underline{p}$ < .0001). Analysis by $\underline{t}$-test indicated that Swedish memory span for both SS and FS was greater than that of FF ($t = 3.46$, $p < .001$, and $t = 2.27$, $p < .05$ respectively), whereas no difference was present between SS and FS.

In short, the results of the memory span task were relatively straightforward. Memory span was larger in the respective dominant languages of SS and FF bilinguals, whereas FS bilinguals obtained an equivalent memory span in Finnish and Swedish. All bilingual types performed equivalently in Finnish and no difference in Swedish memory span was present between SS and FS who in turn obtained larger memory spans in Swedish relative to FF.

4.2.3: Discussion

Despite a shorter articulation time in Finnish than Swedish FS performed equivalently between the languages in the memory span task, thus, speech time did not predict memory span for this bilingual type. Speech time, however, predicted memory span performance for both FF and SS bilinguals. It should be noted, however, that for FF and SS language dominance and the strength of long term representations were likely to have been confounded: a suggestion evidenced most clearly by the finding that FF performed significantly worse in Swedish in both the speech rate and memory span tasks compared to SS and FS. This made it difficult to determine which of the factors exerted a greater influence on memory span performance.

SS bilinguals obtained equivalent memory spans in Finnish compared to FF and FS but articulated Finnish words slower than either of these bilingual types. Therefore for SS, although articulation time predicted memory span at the within-group level, poorer performance in Finnish relative to the remaining groups did not impair memory span performance in Finnish at the between group level. This was added indication that speech time did not account for all the variance in the memory span task. Further support for the notion that speech time and memory span were not causally related was obtained in the finding that although Grade 9 subjects articulated Finnish words faster than Grade 6 subjects no corresponding difference was present in the memory span task.

For the FS bilingual type both speech time and memory span were equivalent to performance in the respective dominant languages of the SS and FF controls. This indicated that, as far as speech time was concerned, FS bilinguals displayed a high level of competence in both languages and made the possibility that performance may have been compromised by discrete levels of fluency between Finnish and Swedish unlikely. It seemed plausible, however, that for FS the strength of long term representations may have been stronger in Swedish than Finnish as a result of receiving schooling in this language. Under these circumstances if speech time was an influential determinant of memory span at either the subvocal rehearsal or speech output levels, a shorter speech time in Finnish may have attenuated the memory span advantage for Swedish and may have been responsible for the observed equivalence in memory span between the languages.

In order to examine the possibility that an interaction between the speech time and long-term representation factors may have been responsible for the equivalence between Finnish and Swedish memory span for FS, in Experiment 2 non word stimuli were used. This manipulation of lexicality controlled for differences in the strength of long-term representations between the languages. Under these circumstances if the effect of stronger long-term representations in Swedish was attenuated by faster speech rate for Finnish for FS in Experiment 3 speech time should be a reliable predictor of the relationship between the languages in the memory span task. Such a finding would provide support for the role of long-term representational factors independent of speech rate on bilingual memory span performance.

4.3: EXPERIMENT 4

4.3.1: Method

Subjects

The same subjects that participated in Experiment 1 were tested after approximately a two week interval.

Materials & Procedure

Four non word pools consisting of 8 short (1 syllable) and 8 long (3 syllable) phonotactically legal Finnish and Swedish non words (Appendix 2.4) were constructed with assistance from Finnish-and Swedish-speaking linguists. The non word pairs and sequences were formed in the manner described in Experiment 3. First measures of memory span were taken. Before testing the Experimenter read the non words in each condition individually and subjects asked to repeat these. A new non word was not introduced until it was established that subjects could pronounce the previous item clearly. Following the memory span task measures of speech time for each set of non words were taken. All other procedural details were identical to those described for Experiment 3.

4.3.2: Results

Articulation Time

The articulation time data were averaged and converted into measures of time per digit and are summarised by bilingual type and grade in Figures 4.3 and 4.4. These data were subjected to a four-way analysis of variance in which grade (6 or 9) and bilingual type (FF, FS, or SS) were between-subjects factors and language (Finnish or Swedish) and non word length (short or long) were within-subjects factors. The results indicated a main effect of language (F (1, 66) = 477.05, $p < .0001$) with a shorter articulation time in Finnish (472 msec/item) than Swedish (653 msec/item). The two-way interactions between grade and language (F (1, 66) = 4.73, $p < .05$), bilingual type and language (F (2, 66) = 19.51, $p < .0001$), bilingual type and word length (F (2, 66) = 4.06, $p < .05$), and language and word length (F (1, 66) = 39.945, $p < .0001$) were reliable. None of the three-way or four-way (F (2,66) = 2.10) interactions were reliable.

Analysis of the interaction between grade and language by simple main effects indicated a difference in articulation time between the grades for Swedish (F (1, 132) = 6.22, $p < .05$, means grade 6 = 685, grade 9 = 621 msec/item) but not Finnish. A language difference was present at both the grade 6 (F (1, 66) = 288.38, $p < .0001$) and grade 9 (F (1, 66) = 193.39, $p < .0001$) levels with shorter articulation time for Finnish than Swedish.

Analysis of the interaction between bilingual type and language indicated a language difference was present for all bilingual types (all $p < .0001$) with a shorter articulation time in Finnish than Swedish. Articulation time in Finnish varied as a function of bilingual type (F (2, 132) = 5.889, $p < .01$) but no difference was present for Swedish. Analysis by t-test indicated that FF (440 msec/item) and FS (442 msec/item) articulated Finnish non words faster than SS (535 msec/item, both $p < .05$).

Analysis of the interaction between bilingual type and word length revealed a difference between bilingual type for long non words (F (2, 132) = 3.80, $p < .05$) but not for short non words. Analysis by t-test indicated that the only difference present was between FS and SS ($p < .05$) with FS (680 msec/item) articulating long non words faster than SS (766 msec/item). Short non words were articulated faster than long non words by all bilingual types ($p < .0001$).

Analysis of the interaction between language and word length indicated that both short (F (1, 132) = 155.71, $p < .0001$) and long non words (F (1, 132) = 428.51, $p < .0001$) were articulated faster in Finnish than Swedish. Word length effects were present for both Finnish (F (1, 132) = 461.86, $p < .0001$) and Swedish (F (1, 32) = 829.88, $p < .0001$).

To summarise, articulation time was shorter in Finnish than Swedish for all bilingual types and short non words were consistently articulated faster than long non words. Performance across bilingual types was equivalent with the exception of SS who were slower in articulating non words in Finnish than both FF and FS. An effect of grade was present for Swedish with non words articulated faster by grade 9 subjects than grade 6 subjects.

Memory Span

The memory span data were subjected to a corresponding four-way analysis of variance and are summarised in Figs 4.3 and 4.4. The main effects of grade (F (1, 66) = 24.42, $p < .0001$), language (F (1, 66) = 115.01, $p < .0001$), and word length (F (1, 66) = 198.89, $p < .0001$) were reliable. Grade 9 subjects (3.99) obtained larger memory spans than grade 6 (3.37) subjects, memory spans were larger in Finnish (3.98) than Swedish (3.37), and more short non words (4.12) were recalled than long non words (3.23). The two-way interactions between bilingual type and language (F (2, 66) = 13.4, $p < .0001$), bilingual type and word length (F (2, 66) = 4.13, $p < .05$), and language and word length (F (1, 66) = 21.75, $p < .0001$), were reliable. None of the three-way or four-way (F (2, 66) = 1.80) interactions were reliable.

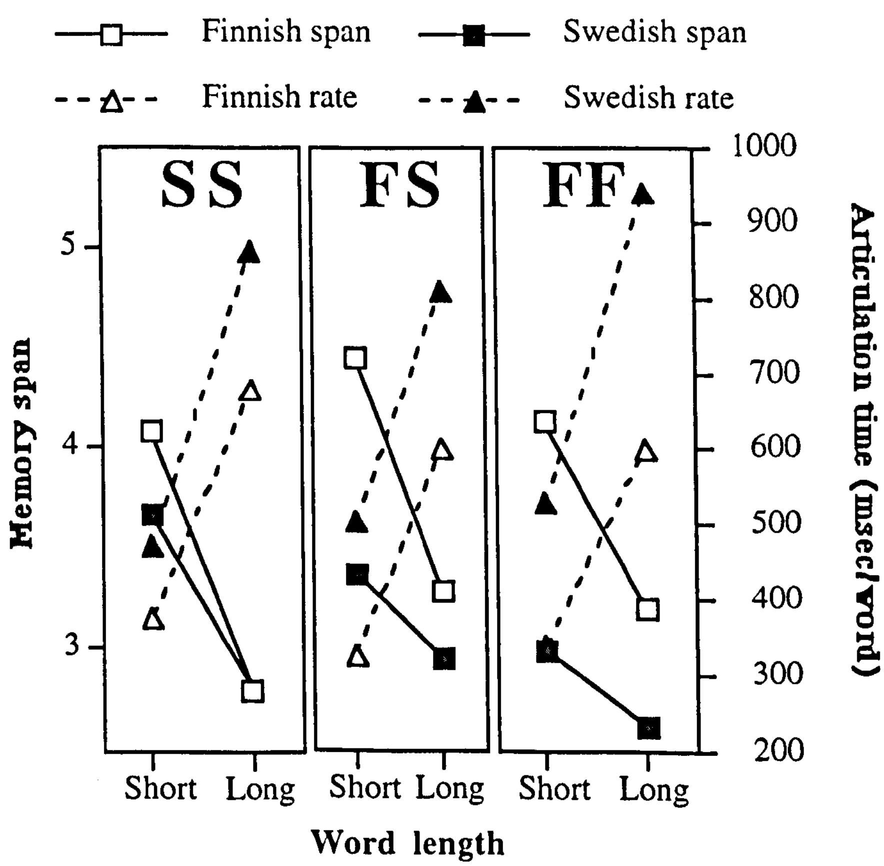

Figure 4.3: Mean articulation time (msec/word) and memory span for short and long non words in Finnish and Swedish for three Grade 6 bilingual types.

Analysis of the interaction between bilingual type and language by simple main effects indicated a language difference for all three bilingual types with memory spans in Finnish larger than in Swedish (means FS = 4.09 and 3.42, $p < .0001$; SS = 3.75 and 3.53, $p < .05$; FF = 4.09 and 3.17 respectively). No differences between bilingual types were present for either language.

Analysis of the interaction between bilingual type and word length indicated differences in memory span as a function of word length for all three bilingual types with memory span for short non words larger than long non words (means FS = 4.18 and 3.33, $p < .0001$; SS = 4.21 and 3.07, $p < .0001$; FF = 3.98 and 3.28 respectively). No differences between bilingual type were present for either word length.

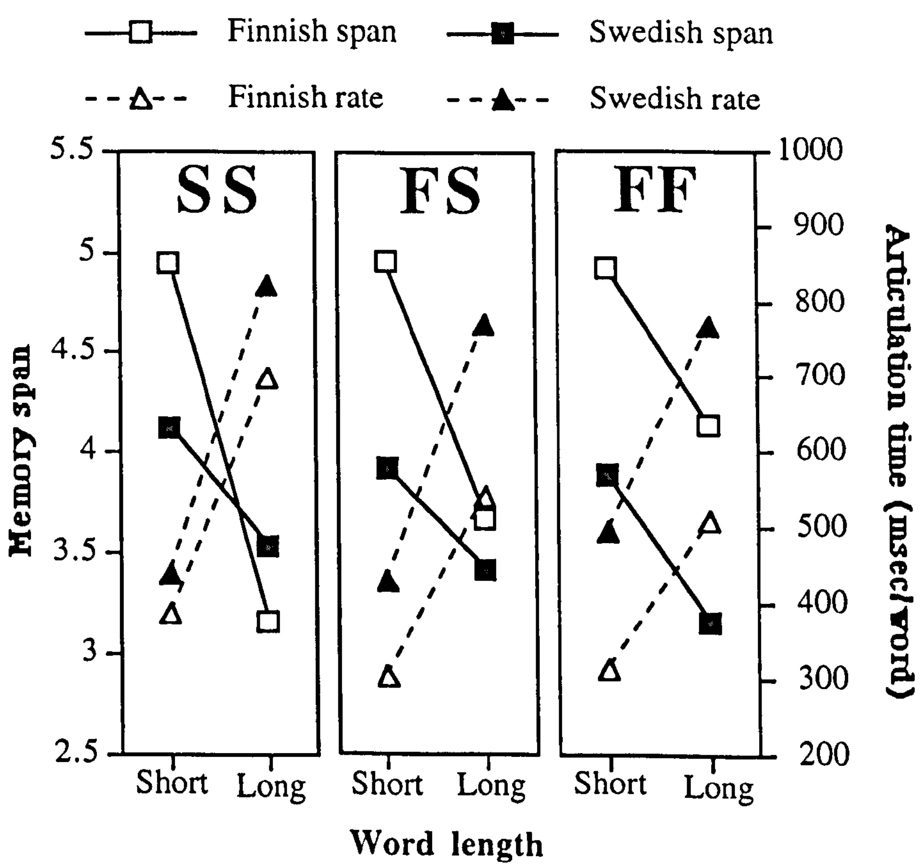

Figure 4.4: Mean articulation time (msec/word) and memory span for short and long non words in Finnish and Swedish for three Grade 9 bilingual types.

Analysis of the interaction between language and word length indicated a difference between Finnish and Swedish for both short (F (1, 132) = 109.35, $p <$ .0001, means = 4.58 and 3.66 respectively), and long non words (F (1, 132) = 10.90, $p < .01$, means = 3.38 and 3.08 respectively). An effect of word length effect was present for Finnish (F (1, 132) = 169.87, $p < .0001$) and Swedish (F (1, 132) = 38.65, $p < .0001$) with memory span greater for short non words in both cases.

The results of the non word memory span task were relatively straightforward. The grade factor did not interact with any other factor and so the effect was clear: memory span was larger for Grade 9 subjects compared to Grade 6 subjects. Memory span was greater for short non words relative to long non words, and for Finnish relative to Swedish. No differences in performance across bilingual type were present for either Finnish or Swedish.

4.3.3: Discussion

The results of Experiment 4 indicated that articulation time was a reliable predictor of memory span for all three bilingual types for non word stimuli . When the differential in the strength of long-term representations between the languages was controlled, the FS group obtained larger memory spans in the language in which articulation time was shorter. This finding suggested that the equivalence in memory span between Finnish and Swedish present in Experiment 3 was likely to be a consequence of an attenuation of the stronger long-term representations in Swedish by faster speech rate in Finnish.

An effect of grade was present for the memory span task with Grade 9 subjects obtaining larger memory spans than Grade 6 subjects, whereas the effect of grade in the articulation task was limited to the Swedish items. In addition, no differences were present between bilingual types in the memory span task, whereas in the articulation rate task SS were slower in articulating non words in Finnish than both FF and FS. These findings suggested that even for non word stimuli speech rate did not account for all the variance in memory span.

4.4: DISCUSSION OF EXPERIMENTS 3 & 4

The motivation for these studies was to examine the contribution of long-term memory representations in moderating the relationship between speech rate and memory span in bilinguals. The results of the first two studies presented in this thesis showed that both adult (Experiment 1) and children (Experiment 2) members of the FS bilingual type displayed an exceptionally high level of bilingual competence as quantified by an equivalence in digit span between the languages. However, it was not possible in these initial studies to extricate the relative contribution of speech rate and long-term representations in determining bilingual memory span. That is, it could not be established whether the equivalence in performance by these individuals was a consequence of a high level of bilingual competence or whether a word length advantage for Swedish digit names compensated for a lower proficiency in the same language.

Experiment 3 examined the relationship between articulation time and memory span for short and long words in Finnish and Swedish. In order to exclude the possibility that FS memory span performance may have been affected by discrete levels of verbal fluency between the languages the measures of speech time for this group were compared to that of control groups consisting of asymmetric bilinguals with native fluency in either Swedish (SS) or Finnish (FF). As expected, both SS and FF articulated words faster in their dominant language in the speech time task and FS performed faster in Finnish than Swedish. Speech time predicted the relationship between the languages for the controls whereas FS bilinguals obtained equivalent memory spans between the languages. Now, the results of the speech task indicated that the FS group articulated Swedish and Finnish words at equivalent rates to control performance in the dominant language it was therefore concluded that an unbalanced level of bilingual competence did not affect performance for this group. The results of the FS bilingual type, thus, indicated that memory span was not exclusively determined by the rate of subvocal rehearsal and phonological loop capacity.

It was hypothesised in Chapter 3 that the equivalence in memory span observed for FS bilinguals may have resulted from a combination of stronger long-term representations for Swedish words and the attenuation of this advantage by a faster speech rate for Finnish. A useful way of testing this notion would have been to compare performance by FS to a similar group of bilinguals that spoke Swedish at home and Finnish in school (a putative SF group). If the assumption that stronger long term representations are likely to be engendered in the language in which schooling is received and that speech rate may be faster in the language of the home are correct, ceteris paribus we would expect SF bilinguals to obtain both faster speech rate and larger memory span in Swedish. However, in Finland bilinguals of the SF type are relatively rare, so in Experiment 4 we opted to examine the effect of long-term representations by repeating Experiment 3 but substituting word stimuli for non words: a manipulation that equated the levels of long-term representation between the languages. The results showed that non word articulation time predicted memory span performance for all three bilingual types and indicated that, when the long term representations ceased to be of consequence, the between-language relationship for the articulation rate task was preserved for the memory span task.

It is possible that a shorter articulation time and larger memory span in Finnish non words may have resulted from the Finnish items being either easier to articulate or more readily identified with real words and that the pattern of performance in Experiment 4 may have been influenced by factors other than speech rate. While this was a possibility, adequate measures were taken to equate the non word items by involving the independent expertise of Finnish- and Swedish-speaking linguists. Nevertheless, further research might consider the use of more objective measures of equivalence between non words such as bigram frequency. This could open a future prospective line of enquiry involving the manipulation of non word difficulty, however defined, to ascertain the relative contribution of long-term knowledge of the dominant and less dominant languages on bilingual information processing.

The comparison of performance between grade levels revealed a level of variation between tasks for both experiments. In Experiment 3, Grade 9 articulated Finnish and Swedish long words faster than Grade 6 and no difference between grades was present in the memory span task, whereas in Experiment 4, Grade 9 subjects articulated Swedish non words faster than Grade 6 and memory span was greater for Grade 9 for both languages. The sum of these findings added support for the view that for the present bilinguals memory span was not exclusively determined by speech rate. Although the development of monolingual speech rate and the impact of this variable on memory capacity has been extensively investigated (e.g., Hulme and Muir, 1985; Henry and Millar, 1991) less attention has been paid to the relationship between these variables in bilinguals and could be a line of prospective inquiry.

To summarise, taken together, the results of Experiments 3 and 4 converged with several recent findings (Hulme et al., 1991, 1995) in that they demonstrated the involvement of long-term factors in determining memory span capacity. The performance by the FS bilingual type in Experiment 3 was an interesting extension to a finding by Hulme et al. (1991) that memory span was greater for words than non words when the items were matched for articulation duration. By contrast, in Experiment 3 it was found that despite differences in articulation time for words, memory span between the languages was equivalent. These findings provided strong evidence of a dynamic interplay between speech rate and long-term factors in determining memory capacity and served to moderate the notion that bilingual digit span effects may be attributed exclusively to differences in word length between languages.

Chapter 5

Eye Movements and the Processing of Numerals

The findings of Experiment 1 demonstrated that numeral reading time was a reliable predictor of visual digit span for Arabic numerals as performance on the reading task was inversely related to performance on the digit span task. Furthermore, the finding that the introduction of a secondary task involving articulatory suppression removed the language difference supported the view that bilingual digit span performance was moderated by phonological loop functioning. Both findings were consistent with those of Chincotta & Hoosain (1995). The results of Experiment 2 showed that Finnish-mother tongue--Swedish-schooled bilinguals, obtained equivalent digit spans between the languages despite a faster articulation time for Swedish. For this group then, a recognition-free estimate of speech rate (a more accurate index of subvocal rehearsal rate) did not predict auditory digit span, whereas digit word reading time did. This finding suggested that the bilingual digit span effect was mediated, in part, by processes unrelated to phonological loop functioning and the rate of subvocal rehearsal. This interpretation was supported by the findings of Experiments 3 and 4 that demonstrated the contribution of long-term memory representations on memory span performance.

Although the findings of Experiment 2 clearly showed that articulation time did not predict the equivalence in performance between Finnish and Swedish for the FS group, it was difficult to decide which of the two statistical analyses of the reading task data (i.e., separate or combined) was the more appropriate . At the combined level of analysis, numeral reading time predicted performance on the digit span task, whereas a more detailed analysis by bilingual type indicated that digit word reading rate was the more accurate predictor of auditory bilingual digit span for the FS bilinguals. If it is assumed that the combined analysis of performance is the more representative, the conclusion that numeral reading rate is a reliable predictor of bilingual digit span (when measured in both the auditory and visual modalities) is consistent with the findings of Experiment 1 and those of previous studies (Ellis & Hennelly, 1980; da Costa Pinto, 1991; Chincotta & Hoosain, 1995).

This next study examined whether the numeral reading task was an adequate estimate of language differences in the word length of digit names or whether it indexed processes that reflected the relative levels of language fluency in bilinguals. This was achieved by comparing the power of three estimates of numeral processing (eye fixations, articulation time and numeral reading time) in predicting bilingual digit span for numerals. The main question under investigation was whether the language-neutral representation of digits made cognitive demands on processing that were independent of the time required to articulate the items. Such a finding would indicate that numeral reading was a sensitive measure of language proficiency rather than, as had been supposed previously, an appropriate estimate of the language differences in digit word length.

5.1: Eye Movements and Numeral Processing

In Chapter 2 it was suggested that the use of language-neutral representations of digits, as numerals are, when estimating bilingual differences in word length may be injudicious. To explain, the processing of numerals is likely to be prone to Stroop-type interference from the more proficient language when the task is performed in the less proficient one (see, e.g., Gerhand, Derçgowski, & McAllister, 1995). The absence of lexical support in numerals may produce estimates of word length that are relatively insensitive to actual language differences in the articulatory duration of digits. The numeral reading task, therefore, may plausibly be an index of the relative level of competence between the bilingual's languages rather than an a pure estimate of differences in word length.

The on-line measurement of the reading process by means of eye fixations is an ecologically-valid indication of the cognitive processes required for the recognition of the stimuli. As the processing load increases, due to variations in word frequency or predictability for example, so the total fixation time on that word increases. When reading aloud, the voice trails behind the eyes by a couple of words (see, for example, Rayner & Pollatsek, 1989). This is especially the case for material appearing in the middle of sentences (Jarvella, Lundberg & Bromley, 1989). Thus, when an item appearing in the middle of a sentence is articulated, the eyes are gazing at a subsequent item and fixation time is independent of overt articulation. On the other hand, the eye-voice span is at its minimum at the end of a sentence, where the eyes pause to allow the voice to catch up. This direct index of processing suggests that an eye fixation is maintained on an item until processing is completed (see, e.g., Underwood & Batt, 1996).

Previous research on number processing has demonstrated that, under certain circumstances, numbers are phonologically encoded. Pynte (1974), Gielen, Brysbaert and Dhondt (1991), and Brysbaert (1995), for example, have showed that fixation durations on Arabic numerals vary as a function of the syllable length of number names. Numbers with long names received longer gazes than numbers with relatively short names. This was taken as evidence for phonological encoding and the subvocal articulation of numbers during their processing.

In order to examine whether the processing of numerals by bilinguals is similarly affected by the syllable-length or articulatory duration of numerals, direct processing estimates were obtained by adopting the technique of monitoring eye movements of Finnish- and Swedish- dominant, Finnish-Swedish bilinguals. The findings of Experiments 1 - 4 showed that Swedish-dominant, Swedish-Finnish bilinguals resident in Finland performed equivalently to native speakers of Finnish, whereas Finnish-dominant, Finnish-Swedish bilinguals did not achieve native speaker fluency in Swedish. In the present study, therefore, a similar pattern of performance was predicted and the Swedish-dominant group was expected to display a more balanced level of bilingual proficiency than the Finnish-dominant group.

Finnish digit names contain twice as many syllables than their Swedish equivalents (2.33 and 1.22 respectively, Appendix 2.2), thus, an estimation of word length based on syllable count suggested that articulatory durations for Swedish digits would be shorter than Finnish. It was, therefore, predicted that both groups, regardless of language dominance, would articulate digits faster in Swedish than in Finnish. Similarly, if number processing entails a strong phonological component, the length of number names should make the processing of numerals faster in Swedish than in Finnish, as indexed by fixation durations on them. This is implicated by the above mentioned studies. On the other hand, if language fluency is a more relevant factor in determining the relative ease of processing, fixation durations on numerals should be longer in the less dominant language relative to the dominant language for each bilingual group. The contrasting of estimates of on-line processing with measures of recognition-independent articulatory duration and reading time, thus, allowed the question as to whether numeral processing was influenced by factors related to fluency or actual differences in articulatory duration between the languages to be addressed.

5.2: EXPERIMENT 5

5.2.1: Method

Subjects

The subjects were 32 undergraduates from two universities in the city of Turku who volunteered to participate in the experiment. Half of the subjects were recruited from Åbo Akademie, Finland's Swedish language university and were classified as Swedish-dominant. The remaining subjects were students from Turun Yliopisto, a Finnish-medium university and comprised the Finnish-dominant group. All subjects had received schooling in their respective mother tongues and had studied their second language for approximately 9 years.

Apparatus

The eye movements were collected by an EYELINK eyetracker manufactured by SR Research Ltd (Canada). The eyetracker is an infra-red video-based tracking system combined with hyperacuity image processing. There are two cameras mounted on a headband (one for each eye) including two infra-red LEDs for illuminating each eye. The headband weighs 450 g in total. The cameras sample pupil location and pupil size at the rate of 250 Hz. Registration is monocular and is performed for the selected eye by placing the camera and the two infra-red light sources 4-6 cm away from the eye. The resolution of eye position is 15 seconds of arc and the spatial accuracy in the order of 0.5 degrees. The system allows free head motion within a 100 cm cube. Head movements are compensated out with the help of a third camera also mounted on the headband that tracks head movements. The compensation is better than 1 degree over the acceptable range of head motion.

Materials

For the eye tracking experiment, a set of 11 test sentences were written both in Swedish and in Finnish. Each critical sentence comprised two one-digit (1 - 9) Arabic numerals (Appendix 2.5). Thus, each subject provided data for 22 numerals in each language. To ensure accurate recordings of eye fixations on the numerals, the sentences were written using a relatively large font size. For the same reason, spacing between words was enlarged. The critical sentences subtended a maximum of four lines of text on the computer screen.

For the measurement of articulation time, three digit triads were constructed at random without replacement using the digits from 1 - 9. The triads were varied systematically to make a total of nine sets of three triads. For the measurement of numeral reading time, two lists of 100 random digits (1 - 9) were constructed with the restriction that consecutive repetition of the items was avoided as were ascending and descending sequences of more than two items (e.g., 6, 7, 8 or 5, 4, 3) were avoided. The lists were printed in 10 rows each consisting of 10 Arabic numerals (1, 2, 3, etc.).

For the measurement of numeral span in Finnish and Swedish two sets of random digit (1-9) sequences were prepared. Each set commenced with two, 3-digit sequences, followed by two, 4-digit sequences, and so on up to a maximum of two, 12-digit sequences. Digits occurring contiguously, ascending and descending sequences were avoided. A computer was programmed to present the sequences at the rate of one digit per second. Each digit appeared in the same position on the monitor and the presentation sequence was as followed. First the legend READY was presented. This prompted subjects to press a designated key on a computer keyboard after which the presentation sequence consisting of a blank screen (1500 msec), a fixation point (1500 msec), and the digit sequence commenced. Once the sequence was completed the fixation point reappeared (1500 msec) followed by a RECALL prompt.

Procedure

Subjects were tested individually and instructions were given in the dominant language. The subjects were requested to use standard digit names for both languages throughout the test session. First, measures of eye fixation in Finnish and Swedish, blocked by language and counterbalanced were taken. Subjects were instructed to read aloud the sentences at a normal pace and to press a response key connected to the computer when this was completed: after which the next sentence appeared on the screen. Prior to the presentation of each target sentence, a fixation point was displayed on the upper-left corner of the screen. When an eye fixation was identified as coinciding with the fixation marker, the target sentence was presented below the fixation point. Before each language block a computerised calibration of the eyetracker was carried out.

Then, measures of articulation time in Finnish and Swedish blocked by language were taken. The subjects were instructed to remember the three-digit sequence and to articulate it as fast as possible when instructed to do so. Once the digit triad was presented in the target language the Experimenter indicated that articulation should commence. Ten repetitions of the sequence were counted and the total time taken measured by stopwatch. Three articulation measures were taken for each language and counterbalancing was determined by a Latin square .

Next, measures of numeral reading time in Finnish and Swedish counterbalanced by language were taken. Subjects were instructed to read the lists accurately and as quickly as possible pronouncing each digit individually and audibly. The Experimenter indicated when reading should commence and measured the time taken by stopwatch.

Finally, measures of numeral span in Finnish and Swedish were taken. The digit sequences were blocked by language and presented via computer at the rate of one digit per second. Subjects were instructed to rehearse the material in the target language and to recall the sequence verbally and in serial order immediately after the appearance of the RECALL prompt. Subjects continued recalling the digit sequences until two incorrect responses at the same sequence length were made. Numeral span was operationalised as the length of the last correctly recalled sequence. If both sequences at this length were correct a score of 0.5 was added. The task was counterbalanced by language and self-paced in that subjects decided the timing between digit sequences by pressing a designated key on a computer keyboard when the READY prompt appeared.

5.2.2: Results

Eye Fixations

Durations of eye fixations landing on the numerals were used as an on-line processing measure. An eye fixation was considered to be on the numeral, when it was located in a rectangle incorporating the numeral and half of the empty space both to the left and right from the numeral. An example of eye movement data is illustrated in Figure. 5.1. With a viewing distance of 50 cm, the rectangle subtended 4 degrees of visual angle.

Gaze duration, the sum of all fixations landing on the numeral before fixating away from it, was chosen as the critical measure. In most cases, gaze duration was made up of a single fixation. Regressions back to the numeral were rare. The average gaze duration for the numerals was computed for each subject both for Finnish and

Swedish. Only those instances in which at least one fixation on the numeral was present were considered. The probability of leaving the number unfixated was analysed separately.

The gaze durations (msec) were subjected to a two-way analysis of variance in which bilingual type (Finnish- or Swedish-dominant) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factors and is summarised in Figure 5.2. This indicated a reliable main effect of bilingual type (F (1,30) = 11.97, p < .01) with shorter gaze durations for the Swedish-dominant group than the Finnish-dominant group (means = 223 and 288 msec respectively). The interaction between the factors was reliable (F (1,30) = 65.43 p <.0001).

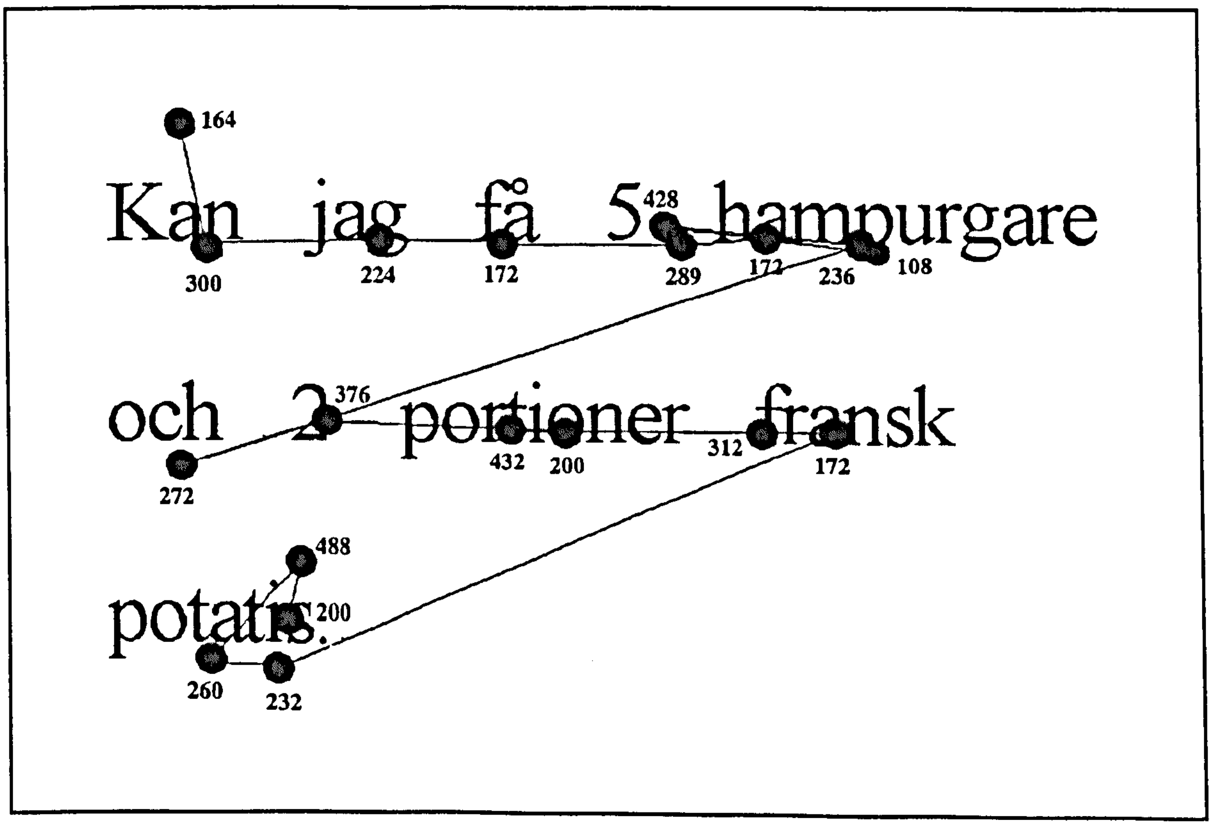

Figure 5.1: An example of the eye movement data for a Swedish sentence as captured by the EYELINK eye tracker. The values nearest the black circles represent the duration (msec) of the fixations.

Analysis of the interaction between bilingual type and language by simple main effects indicated language differences for both the Finnish-dominant (F (1,30) = 46.66, p <.0001) and the Swedish-dominant groups (F (1,30) = 21.41, p <.001). Gaze durations for the Finnish-dominant group were shorter in Finnish than Swedish (233 and 344 msec respectively) and vice versa for the Swedish-dominant group (186 and 261 msec respectively). A between-group difference was present for Swedish (F (1,60) = 51.48, p <.0001) with shorter gaze durations by the Swedish-dominant bilinguals than the Finnish-dominant ones (186 and 233 msec respectively) but not for Finnish, hence the interaction term.

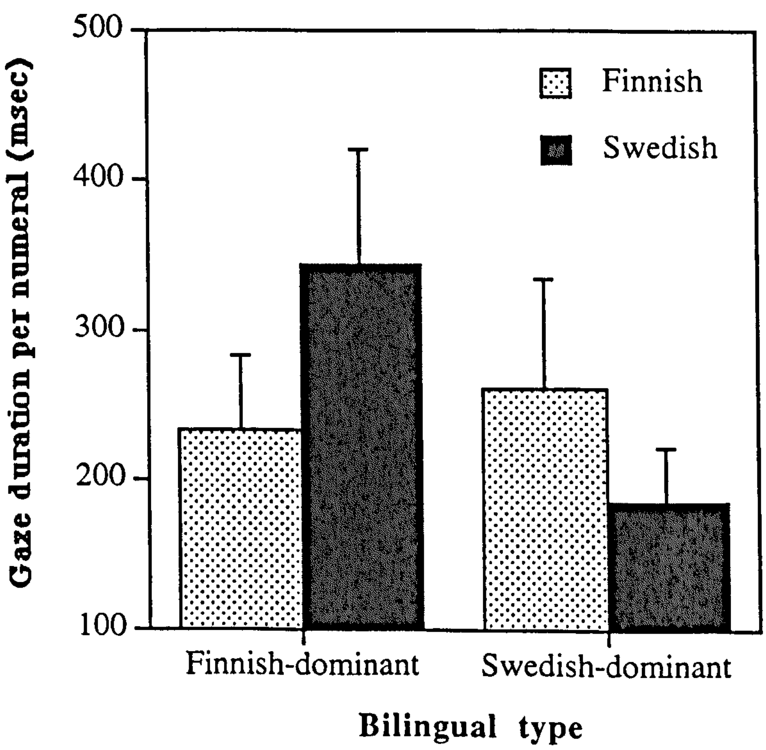

Figure 5.2: Mean gaze duration per numeral (msec) in Finnish and Swedish for Finnish- and Swedish-dominant bilinguals.

The actual number of first forward fixations on the target items in Finnish and Swedish for each subject was calculated as a percentage of the total number of possible fixations (22 for each language block). These data were subjected to a two-way analysis of variance in which bilingual type (Finnish- or Swedish-dominant) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor. The main effect of language was reliable (F (1,30) = 8.46, p < .01) with a higher percentage of fixations for Swedish (80.22 per cent) than Finnish (70.38 per cent). The interaction between the factors was reliable (F (1,30) = 13.31, $p < .001$). Analysis of the interaction by simple main effects indicated a difference between the Finnish-dominant and Swedish-dominant groups for Finnish (F (1, 60) = 4.52, $p < .05$, means = 62.4 and 78.4 per cent respectively) but not for Swedish (F (1, 60) = 1.33, means = 84.56 and 75.86 per cent respectively). A language difference was present for the Finnish-dominant group (F (1, 30) = 21.5, $p < .0001$), but not for the Swedish-dominant group ($F < 1$).

The Finnish-dominant group, thus, fixated on the numerals less frequently in the dominant language than the less dominant one, whereas the Swedish-dominant group performed equivalently between the languages. When performance was specified in Finnish, the Finnish-dominant group had a lower probability of making a fixation on the numeral than the Swedish-dominant group, whereas no between-group was present for Swedish.

The results of the eye tracking study indicated that shorter gaze durations were present in the dominant language of each bilingual type. The magnitude of the language difference was greater for the Finnish-dominant (111 msec) than the Swedish-dominant group (75 msec). The Swedish-dominant group performed equivalently to the Finnish-dominant group in Finnish, whereas the reverse was not so. Finally, for the Finnish-dominant group the between-language difference in the percentage of fixations was 16 per cent, whereas for the Swedish-dominant group this was 10 per cent. Although the analysis by simple main effects indicated that the magnitude of the language difference was not significant for the Swedish-dominant group both trends indicated that the probability of making a fixation on the numeral was influenced by language dominance.

<u>Articulation Time</u>

The data from the articulation task were averaged, converted into measures of time per digit (msec) and subjected to a two-way analysis of variance in which bilingual type (Finnish- or Swedish-dominant) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor and are summarised in Fig 5.3. This indicated a main effect of language (F (1,30) = 133.13, $p < .0001$) with a shorter articulation time in Swedish than Finnish (means = 272 and 349 msec respectively). The interaction between the factors was reliable (F (1,30) = 39.98, $p < .0001$).

Analysis of the two-way interaction by simple main effects indicated a shorter articulation time for the Swedish-dominant group than the Finnish-dominant one for Swedish (F (1,60) = 14.67, $p < .001$, means = 230 and 314 msec respectively). No difference between the groups was present for Finnish (F (1,60) < 1) and hence the interaction term. Digits were articulated faster in Swedish than Finnish by both the Finnish-dominant (F (1,30) = 13.60, $p < .001$, means = 314 and 349 msec respectively) and Swedish dominant groups (F (1,30) = 159.51, $p < .0001$, means = 230 and 350 msec respectively).

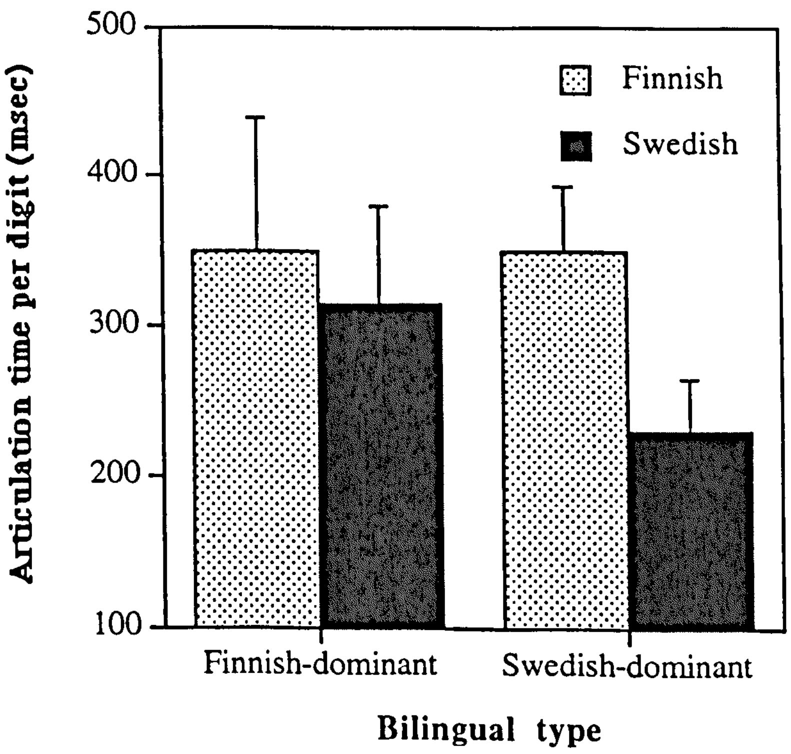

Figure 5.3: Mean articulation time per digits (msec) in Finnish and Swedish for Finnish- and Swedish-dominant bilinguals.

The results of the articulation task indicated that Swedish digits were articulated faster by both bilingual types regardless of language dominance. The magnitude of the difference was greater for the Swedish-dominant group (120 msec) than for the Finnish-dominant group (35 msec).

Reading Time

The data from the reading task were converted into measures of time per digit (msec) and subjected to a two-way analysis of variance in which bilingual type (Finnish- or Swedish-dominant) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factor and are represented in Fig 5.4. This indicated a reliable main effect of bilingual type (F (1,30) = 16.88, $p < .001$) with a shorter reading time for the Swedish-dominant than the Finnish-dominant group (means = 399 and 506 msec respectively). The interaction between the factors was reliable (F (1,30) = 61.97, $p < .0001$).

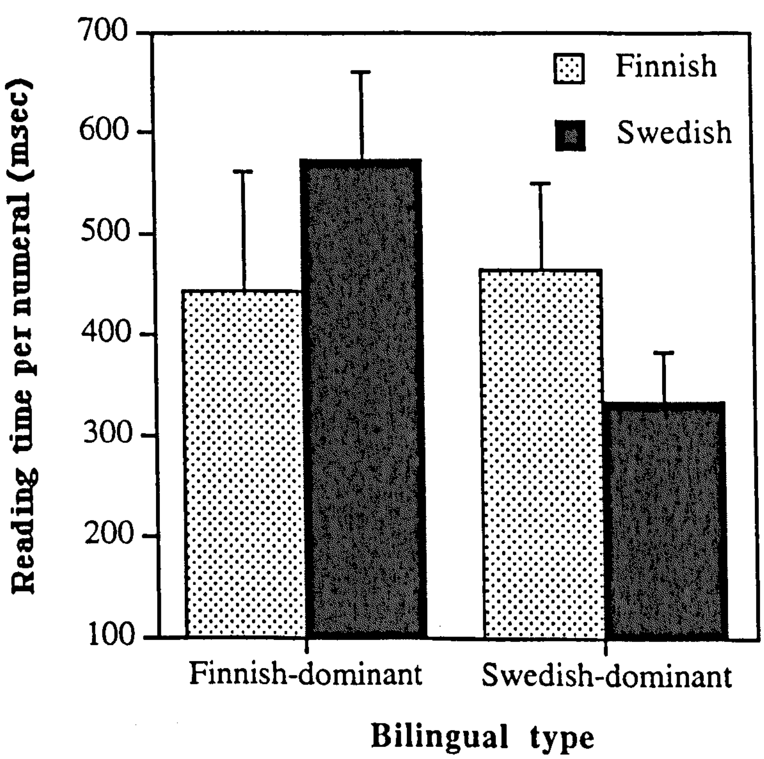

Figure 5.4: Mean reading time per numeral (msec) in Finnish and Swedish for Finnish- and Swedish-dominant bilinguals.

Analysis of the interaction between bilingual type and language by simple main effects indicated language differences for both the Finnish-dominant (F (1,30) = 30.32,

$p < .0001$) and the Swedish-dominant groups (F (1,30) = 31.66, $p < .0001$). Reading time for the Finnish-dominant group was shorter in Finnish than Swedish (444 and 573 msec respectively) and vice versa for the Swedish-dominant group (333 and 465 msec respectively). A between-group difference was present for Swedish (F (1,60) = 58.53, $p < 0001$) with a shorter reading time by the Swedish-dominant bilinguals than the Finnish-dominant ones (333 and 573 msec respectively) but not for Finnish (F (1,60) < 1) and hence the interaction term.

The results of the reading task indicated that each bilingual type read digits faster in their respective dominant languages and that the magnitude of the language difference was greater for the Swedish-dominant group (240 msec) than the Finnish-dominant group (132 msec).

To summarise, the results of the eye-tracking study and numeral reading task showed that each bilingual type obtained shorter gaze durations and shorter reading times in their respective dominant languages. The results of the articulation task, however, showed that performance was faster for Swedish than Finnish by both groups. The Finnish-dominant group, thus, had a shorter articulation time in their second language.

Memory Span

The memory span data were subjected to a two-way analysis of variance in which bilingual type (Finnish- or Swedish-dominant) was a between-subjects factor and language (Finnish or Swedish) was a within-subjects factors and are summarised in Fig 5.5. This indicated a reliable main effect of language (F (1,30) = 5.60, $p < .05$) with a larger span in Swedish than Finnish (means = 6.11 and 5.61). The interaction between factors was reliable (F (1,30) = 19.68, $p < .0001$).

Analysis of the interaction between bilingual type and language by simple main effects indicated that performance in Finnish was equivalent between the groups (F < 1), whereas the Swedish-dominant group obtained a larger digit span than the Finnish-dominant group in Swedish (F (1,60) = 14.52, $p < .001$). The Swedish-dominant group obtained a larger memory span in Swedish than Finnish (F (1,30) = 23.14, $p <$ .0001, means = 6.88 and 5.44 respectively), whereas no difference between the languages was present for the Finnish-dominant group (F (1,30) = 2.14, means Finnish = 5.78, Swedish = 5.34). Although the analysis of the interaction indicated the absence of a language difference for the Finnish-dominant group, inspection of the means indicated that the statistical suggestion of equivalence may have resulted from variation in the magnitude of the language difference between the Swedish-dominant group (1.44) and the Finnish-dominant group (.44). This was tested by a planned contrast which indicated that for the Finnish-dominant group the difference between Finnish and Swedish was marginal (t = 1.58, $p < .07$).

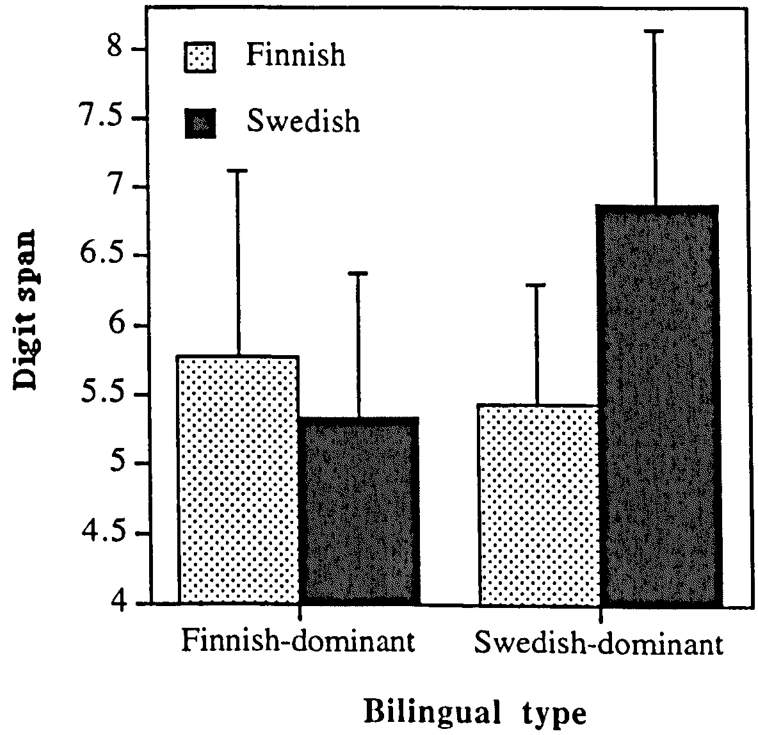

Figure 5.5: Mean digit span for numerals in Finnish and Swedish by Finnish- and Swedish-dominant bilinguals.

The results of the memory span task indicated that the Swedish-dominant group had a larger digit span in the dominant language, whereas for the Finnish-dominant group a marginally larger span for Finnish than Swedish was present.

5.2.3 Discussion

The question addressed by Experiment 5 was relatively straightforward. If the bilingual digit span effect is mediated by word length between languages as indicated by the findings of Experiment 1, why is numeral reading (a task involving recognition processes) a reliable predictor of between-language differences in digit span in bilinguals? It was posited that one explanation could be that numeral reading time is heavily influenced by the level of relative bilingual fluency and, thus, does not provide an adequate estimate of the actual variation in word length between languages. That is, the cognitive demands required in the retrieval from the bilingual lexicon of phonological representations for language-neutral stimuli are such that cross-linguistic variation in articulatory duration may be masked. This view was supported by the finding in Experiment 1 that reading time for digit words differed so markedly to that for numeral stimuli. If this view is correct, the estimation of language differences on the basis of numeral reading tasks in Experiment 1 (and other studies, e.g., Ellis & Hennelly, 1980; Chincotta & Hoosain, 1995) may have resulted in the misattribution of the bilingual digit span effect to the variation in word length and the rate of subvocal rehearsal between Swedish and Finnish.

This notion was tested by applying the technique of monitoring eye movements to obtain a direct measure of numeral processing and contrasted this with a recognition-independent estimate of digit word length. The results indicated that Finnish- and Swedish-dominant bilinguals had shorter gaze durations in their respective dominant languages. This finding suggested that the processes associated with the retrieval of phonological representations of numerals made greater cognitive demands when performance was specified in the less dominant language. This was in stark contrast to the results of the articulation time task where, regardless of language dominance, both groups articulated digits faster in Swedish than Finnish. Numeral reading performance mirrored that of the eye-movement task and indicated that the underlying processes involved in these tasks were mediated by cognitive loads associated with recognition and retrieval processes rather than actual articulatory duration.

The results of the memory task indicated that the Swedish-dominant group had a larger digit span in Swedish than Finnish, whereas the Finnish-dominant group obtained a marginally larger span in Finnish than Swedish. Thus, a word length advantage for Swedish digits was not sufficient to occasion a larger digit span in the same language. The absence of a clear statistical advantage for Finnish over Swedish in the digit span task for the Finnish-dominant group constrained the degree to which it could be argued that bilingual digit span effects are mediated exclusively by the level of relative fluency. Instead, this finding suggested that a shorter articulation time for Swedish digits exerted an attenuating effect over the stronger long-term representations for Finnish digits.

The present findings suggested that studies that have estimated word length differences for digit names between languages on the basis of numeral reading tasks (e.g., Ellis & Hennelly, 1980; Chincotta & Hoosain, 1995; Experiment 1) should not be interpreted as a demonstration of the mediating effects of articulatory duration and subvocal rehearsal on the bilingual digit span effect. The results of the eye movement study showed that greater cognitive demands are required for the processing of numeral stimuli in the less dominant language independent of articulation. Eye fixations were collected as subjects read aloud, therefore, these differences must be associated with post-recognition processes such as phonological recoding and, perhaps, lexical search and compilation of the articulatory output codes. The identical outcome, in terms of the relationship between the dominant and less dominant languages, between the eye fixation and numeral reading tasks suggested that the latter measure was influenced by retrieval processes rather than articulatory duration.

The present findings necessitated a modified interpretation of the bilingual digit span effect. Namely, bilinguals are likely to obtain a larger digit span in the language in which fluency for numbers is greatest: the language of schooling being an important factor in determining this specific type of fluency (Experiment 1). There are circumstances, however, in which a word length advantage in the bilingual's less dominant language may attenuate the natural advantage of the dominant language in digit span tasks (although the precise parameters that determine such relationships have yet to be specified). This explanation is supported by a study of English- and Mandarin-dominant, Mandarin-English bilinguals by Elliot (1992) in which both groups obtained a faster articulation time in Mandarin than English (see also Experiment 2). However, the Mandarin-dominant group obtained a larger auditory digit span in Mandarin, whereas the English-dominant group obtained equivalent digit spans between the languages.

An important question that lay beyond of the scope of the present study remained to be answered. Namely, if bilingual digit span effects are not mediated exclusively by variation in word length, why does articulatory suppression eliminate language differences in numeral span tasks? As discussed above, the effectiveness of articulatory suppression in eliminating the effects of word length in bilingual digit span tasks is marked by inconsistency and varies according to the manner in which digits are represented. The answer to this question may, in part, be a procedural one. That is, in bilingual digit span studies, the pace at which the articulatory suppression phrase is uttered has not been monitored closely: this is also true of a number of monolingual studies. It is possible that strategies involving an imperceptible decrease in the rate of suppression may be used to compensate performance when cognitive demands are high (as in the case of the less dominant language) and this may result in comparable levels of performance between the dominant and less dominant languages. This question was addressed in Chapters 7 and 8.

In short, although numerals were articulated faster in Swedish than Finnish by both bilingual groups, when processing involved the recognition of print, the language-neutral status of numerals made greater processing demands when performance was specified in the less dominant language. The differential levels of cognitive load involved in accessing the appropriate phonological representation prior to speech production indicated that the numeral reading task indexes the relative fluency between the bilingual's languages rather than cross-linguistic differences in articulation time as has been previously supposed (e.g., Ellis & Hennelly, 1980; Chincotta & Hoosain, 1995, Experiment 1). The present findings were in keeping with those of Hulme et al. (1991, 1995) in that they demonstrated the involvement of factors independent of word length in memory span tasks and, thus, contributed towards moderating the role of articulatory duration in mediating the bilingual digit span effect. This is not to say that the word length variable is without influence, it clearly underlies the phenomenon. However, it has yet to be established convincingly whether linguistic factors alone are sufficient to overcome the role of long-term representations and fluency in mediating bilingual memory capacity.

Chapter 6

Bilingual Memory Span and Digit Representation

The findings of the studies presented in Chapters 2, 3 and 5 suggested that the representation of digits as either numerals (e.g., 1, 2, & 3) or digit words (e.g., one, two, & three) is a variable that affects reading time. To recapitulate, the findings of Experiment 1 demonstrated that the relationship between performance in Finnish and Swedish on a numeral reading task varied as a function of bilingual type, whereas performance on a digit word task did not vary across subjects with a consistently shorter reading time for Swedish (the word-length advantaged language according to syllable count) compared to Finnish. This pattern of results was interpreted as reflecting two possibilities.

First, it seemed plausible that language-neutral numeral representations of digits are prone to Stroop-type interference from the dominant language when performance is specified in the less-dominant language. The findings of the eye-tracking study (Experiment 5) supported the notion that additional cognitive demands independent of word length and articulation duration are present when numerals are processed in the less-dominant language as the relationship between the languages on the reading task mirrored performance on the articulation-independent measure of gaze duration and not articulation time.

On the basis of these results it was concluded that the relationship between numeral reading rate and bilingual digit span (both auditory and visual) may be accounted for in terms of the level of relative fluency between the bilingual's languages. In other words, it seemed likely that numeral reading time was a measure of language proficiency rather than an adequate estimate of cross-linguistic difference in the articulation duration of digit names. Under these circumstances it seemed injudicious to interpret findings that numeral reading time is a predictor of bilingual digit span as support for the view that bilingual digit span effects are moderated by word-length and the rate of subvocal rehearsal. Although it was suggested in Chapter 5 that bilinguals are likely to obtain larger digit spans in the language in which the are most fluent, the likelihood that shorter articulation durations in the less-dominant languages attenuate a natural disadvantage for memory span performance in the same language is an important caveat (Chapter 4).

Second, the finding that reading time varied so dramatically as a function of number representation suggested that, within the working memory paradigm, digit span performance could vary correspondingly dependent upon whether numeral or digit word stimuli were presented. If this notion were extrapolated to the findings of Experiment 1, it was plausible that digit word span could have been consistently greater in Swedish for all the bilingual types regardless of the effects of mother tongue and language of schooling.

The variation in terms of digit representation and modality both across and between studies of bilingual digit span has been high and is described in some detail below. It was, thus, reasoned that the absence of consistent findings in terms of the effects of articulatory suppression on the language relationship in digit span tasks could be a consequence of procedural differences between studies.

Experiment 6, therefore, examined the relationship between numeral and digit word reading time and memory span for the same stimuli in Spanish-dominant, Spanish-English bilinguals in order to establish whether between language performance varied for numerals and digit words. The effect of articulatory suppression as a function of digit representation was examined in Experiment 7 to ascertain whether this secondary task had differential effects on the between language relationship for numerals and digit words.

6.1: Numeral and Digit word Span

Bilingual digit span studies have identified the effects of familiarity arising from practice in counting and computation associated with schooling (Experiment 1) and individual differences in articulation duration for digit names between languages as important factors determining bilingual span performance (Chincotta & Hoosain, 1995). These variables are likely to affect bilingual span performance by contributing to the speed of articulation for digits. The findings of Experiments 3 and 4, however, also suggested an independent contribution of non-temporal factors such as long-term memory representations to working memory capacity as may have been expected from the results of monolinguals studies of memory (Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, Brown, & Mercer, 1995).

In the bilingual digit span studies reported to date reading speed for numerals has generally been used as a substitute for other, arguably more precise, estimations of speech rate. Henry (1994) and Hitch, Halliday, and Littler (1989) have suggested that the various methods of estimating speech rate are broadly, if not wholly, equivalent in that the relationship between memory span and speech rate, however quantified, is robust. It is the apparent reliability of numeral reading rate, whatever its shortcomings as an estimate of speech rate, in predicting memory span performance between the languages of the bilingual that merited closer attention. The present study examined the effect of a variable affecting reading rate for digits in bilinguals that had eluded close scrutiny, namely the representation of digits as numerals (e.g., 1, 2, & 3) or digit words (e.g., one, two, & three).

It has been argued in Chapters 3 and 5 that when bilinguals are tested in the less dominant language, the greater level of lexical support available in digit words relative to numerals occasions a decrease in cognitive demands during the recognition and articulation processes which, in turn, results in a faster speech rate for the former stimuli (Chincotta and Hoosain, 1995). In the dominant language, however, the lexical support in digit words is redundant and no difference in reading rate is noted between the digit representations. Alternatively, the reading of language-neutral numeral stimuli may require more complex processing due to possible Stroop-like interference from the dominant language resulting in greater effort in the retrieval of the appropriate words from the bilingual lexicon. Some support for this notion was found in the results of Experiment 5 which demonstrated that the language-neutral status of numeral stimuli made greater cognitive demands that were independent of articulation time when performance was specified in the less-dominant language of Swedish and Finnish bilinguals.

The results of Experiment 1 provided further support for the view that the representation of digits as Arabic numerals or digit words affects reading rate when bilinguals are tested in the less dominant language. In addition, da Costa Pinto (1991) reported that the relationship between reading time for numerals and digit words varied between the languages of Portuguese-English bilinguals. For Portuguese (the dominant language) no difference in reading time was present between numerals and digit words, whereas for English digit words were read faster than numerals. Unfortunately, da Costa Pinto (1991) did not examine the effect of differential reading time in the second language on memory span.

Given the consistent finding of a relationship between numeral reading rate and bilingual memory span a question of some interest was whether memory span in the second language of the bilingual would vary depending on whether the stimuli are numerals or digit words. Experiment 6 examined reading rate for numeral and digit word stimuli using Spanish-dominant, Spanish-English bilinguals. On the basis of da Costa Pinto's (1991) findings, an interaction between language and number representation was expected with equivalent numeral and digit word reading time for Spanish and a shorter digit word reading time than numeral reading time for English. The crucial question under investigation, however, was whether a shorter reading time for digit words in the less dominant language (English) would predict a larger memory span for these items relative to numerals. Given the inverse relationship between speech rate and memory span proposed by working memory theory and consistent findings in the bilingual digit span literature supporting this notion such a finding appeared theoretically possible.

6.2: EXPERIMENT 6

6.2.1: Method

Subjects

The subjects were 20 Spanish-English bilingual students (10 female and 10 male) from Spain and attending a British University under the auspices of the ERASMUS academic exchange program. The sample consisted of equal numbers of Science and Arts/Humanities students. The subjects had studied English for an average of approximately 9 years and were paid for participation.

Materials

For measurement of reading time four lists of 200 numbers varying from 1 to 9 were constructed. Two of the lists consisted of Arabic numerals, the remaining two lists contained digit words in either Spanish or English. Each number occurred with the same frequency in all four lists, ranging from 21 to 24 occurrences. Consecutive repetition of numbers, as well as ascending and descending sequences of more than two digits were avoided. Each list was printed in 20 rows each containing 10 items. Instructions for the reading rate and digit span measures were prepared in both Spanish and English.

For measurement of numeral and digit word span in Spanish and English four sets of random number sequences were prepared. Each set commenced with two, 2 item sequences followed by two, 3 item sequences, and so on to a maximum of two, 12 item sequences. Identical items appearing contiguously and ascending and descending sequences were avoided. The sequences were presented at the rate of one item per second. Each item appeared in the same position on a monitor and the presentation sequence was as follows. First, the legend READY or PREPARADO (the Spanish equivalent) was presented. This prompted the subject to press a key on a computer keyboard after which the presentation sequence then commenced and consisted of a blank screen (1500 msec), a fixation point (1500 msec), and the item sequence. Once the item sequence terminated, the fixation point reappeared for 1500 msec followed by the legend RECALL or RECUERDA prompting subjects to commence recall.

Procedure

Subjects were tested individually by a fluent bilingual and the language of instruction was varied and counterbalanced. First, measures of reading rate for 200 random numerals and digit words in Spanish and English were taken. Subjects read the lists accurately and as quickly as possible pronouncing each digit individually and audibly. List order was counterbalanced by a Latin square and time taken measured by stop watch. Before testing, subjects were given a practice trial on a list of 50 random digits for which language was varied.

Next, measures of digit span for both numerals and digit words in Spanish and English were taken. The sequences of random numerals and digit words were presented via computer. Each condition commenced with two, 2-item sequences, two, 3-item sequences, two, 4-item sequences, and so on to a maximum of 12 items. When presentation of the item sequence terminated, subjects immediately recalled the sequence serially and verbally as quickly as possible. For each condition, subjects continued recalling the item sequences until two incorrect responses at the same length were made.

Before testing subjects were allowed one practice trial in each language for digit sequences of two items. Testing continued until two errors at the same sequence length were made. Memory span was operationalised as the length of the last correctly recalled sequence. If both sequences at the last length were correct a score of 0.5 was added. The order of presentation for language and items was counterbalanced by a Latin square.

6.2.2: Results

Reading Time

The data from the numeral and digit word reading data were converted into reading times per item (msec) and are represented in Figure 6.1. These data were subjected to a two-way analysis of variance in which language (Spanish or English) and item (numerals or digit words) were within-subjects factor. This showed a significant effect of language (F, (1,19) = 72.88, $p < .0001$), with Spanish reading time shorter than English (means = 330 msec/item and 410 msec/item respectively), and of item (F, (1,19) = 53.72, $p < .0001$), with digit words read faster than numerals (means = 344 msec/item and 396 msec/item respectively).

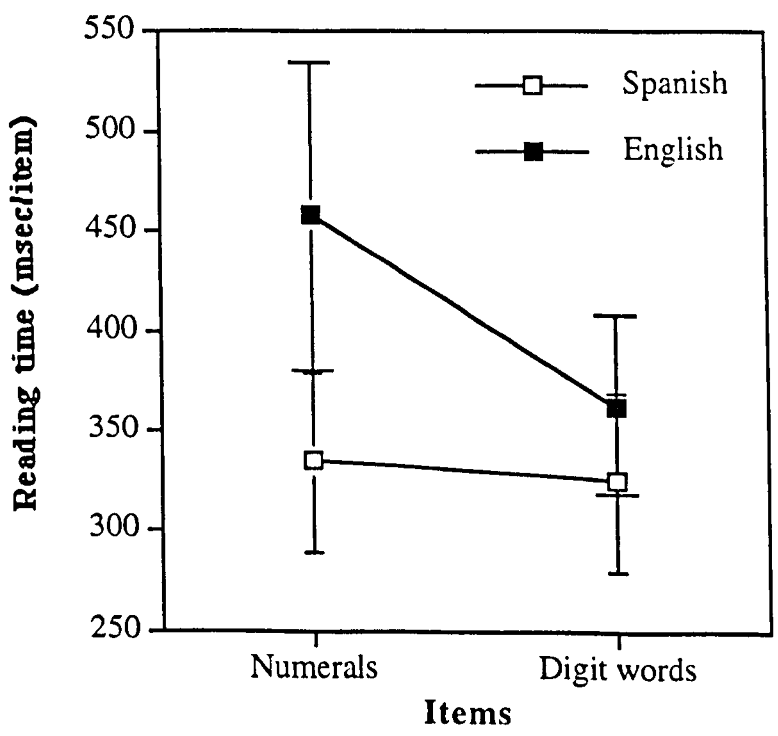

Figure 6.1: Mean reading time (msec/item) in Spanish and English for numerals and digit words.

A reliable interaction between the factors was also present (F, (1,19) = 29.84, $p < .0001$). Analysis of the interaction by simple main effects indicated between language differences for both numeral (F, (1,19) = 84.943, $p < .0001$) and digit word stimuli (F, (1,19) = 8.16, $p < .05$). In both cases Spanish was the language associated with a shorter reading time. A difference in reading time was also present between numerals and digit words for English (F, (1,19) = 87.99, $p < .0001$) but not for Spanish.

Digit Span

The digit span data were subjected to a two-way analysis of variance in which language (Spanish or English) and item (numerals or digit words) were within-subjects factors and are summarised in Figure 6.2. This showed a significant effect of language (F, (1,19) = 14.00, $p < .01$), with digit span greater in Spanish than English (means = 6.20 and 5.59 respectively) and of item (F, (1,19) = 9.29, $p < .01$), with numeral span greater than digit word span (means = 6.06 and 5.73 respectively). The interaction between the factors was not reliable (F, < 1).

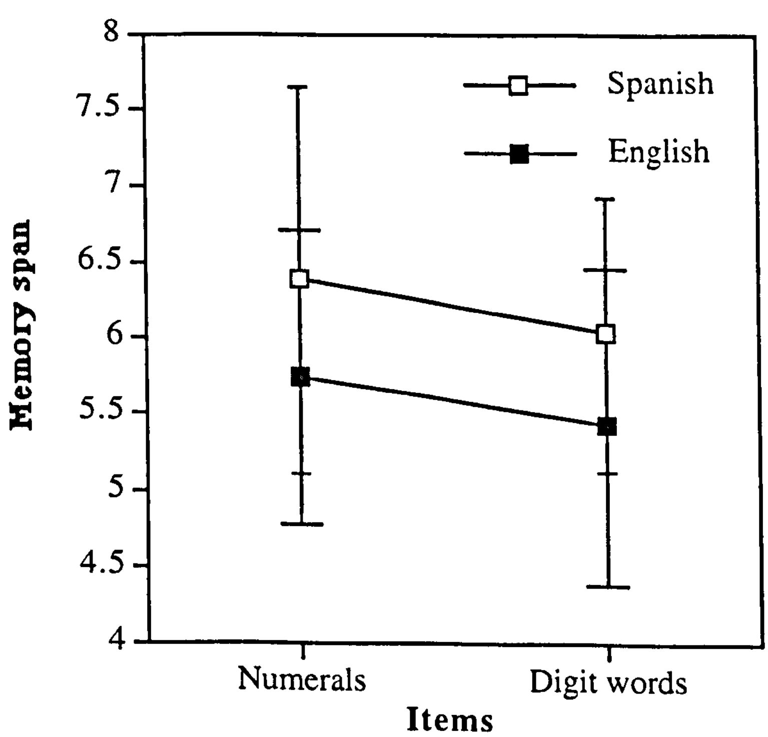

Figure 6.2: Mean memory span in Spanish and English for numerals and digit words.

6.2.3: Discussion

As expected no differences were present between numeral and digit word reading time in the dominant language (Spanish), whereas a shorter reading time was present for digit words compared to numerals when performance was measured for the less dominant language (English). The results of the memory span task indicated larger spans in Spanish than English and this much was predicted by the results of the reading rate tasks that showed overall faster performance in Spanish than English.

The possibility had been considered that a shorter reading time for digit words relative to numerals in English would predict larger memory span for the former. However, the results indicated that numeral span was larger than digit word span and the absence of a qualifying interaction between the factors indicated an equivalent relationship between languages. Therefore, although reading time predicted larger digit spans in Spanish compared to English it did not predict the within-language relationship between numerals and digit words for either language. These findings indicated the involvement of factors other than naming speed and phonological rehearsal in digit span.

A longer reading time in English for numerals relative to digit words could have been occasioned by Stroop-like interference from the dominant language as described in Experiment 5. This may have slowed output as language-neutral items are likely to activate Spanish production codes in preference to English. Digit words, on the other hand, offer more direct support through separate language-specific representations and lexical support and are less likely to activate language output in the dominant language. Digit words, then, engage separate encoding and decoding processes from the outset, whereas numerals are commonly encoded in both languages resulting in consequent delays when output is specified in the less dominant language. Whilst this explanation of the reading rate results was plausible, the question remained as to why corresponding differences in processing between numerals and digit words were not present for the memory span task.

The memory span advantage for numerals over digit words, particularly in the dominant language, was perplexing as the distinct number representations should, arguably, have been recoded into phonological representations with equal facility -- a claim strengthened by the equivalence in between-item reading rate for Spanish. The finding of a numeral advantage in the less dominant language was equally unexpected given that reading rate for digit words was significantly faster than for numerals. So, how may the superiority of numeral span over digit word span, ostensibly unrelated to reading rate, be accounted for?

Before discussing these findings further a potential criticism of Experiment 6 was addressed. It could be argued that when the target language of recall was English, subjects may have encoded the stimuli in the dominant language and translated the sequences into English at the point of recall. Although checks were made to ensure that recall commenced as soon as the sequences terminated and completed as quickly as possible, it was impossible to rule out the possibility that the digit strings were subvocally rehearsed in the non-target language. If such a translation-based strategy was used, a simple explanation for the larger numeral span relative to digit word span in English could be that the coding process was less demanding for the language-neutral stimuli relative to language-specific digit words. In the case of numerals the stimuli are likely activate language representations in Spanish which are then subvocally rehearsed and simply translated at point of recall. English digit words, however, would require extra processing in the decoding of items into equivalent phonological representations in Spanish, subvocal rehearsal in Spanish and translation into English prior to recall.

Whilst this was a plausible explanation for the observed superior numeral span compared to digit word span for English it did not explain why a similar pattern of results was observed for Spanish where the encoding from visual to phonological representations suitable for rehearsal was likely to be equivalent for both numeral and digit word stimuli. In Experiment 7 an articulatory suppression condition was introduced into the design as a means of eliminating the opportunity for the subvocal rehearsal of items in Spanish and translation of the material into English at the point of recall.

6.3: EXPERIMENT 7

Measuring the effect of articulatory suppression on memory capacity for numerals and digit words allowed examination of two separate issues related to working memory interpretations of the bilingual digit span effect. First, articulatory suppression prevents the transformation of visual material into a phonological code through the occupation of the phonological loop. Memory span is, therefore, necessarily mediated by factors other than phonological loop functioning. An examination of memory span performance under articulatory suppression would, thus, provide an indication of the presence of factors other than subvocal speech rate that influence bilingual memory span as posited from the findings of Experiments 2-5.

Second, there is disagreement with regard to the effect of articulatory suppression on bilingual digit span. Ellis and Hennelly (1980), Chincotta and Hoosain (1995), and Experiment 1, found that articulatory suppression eliminated digit span differences for bilinguals displaying a range of bilingual competence and concluded that the basis of the difference in the memory span between the languages was phonological. Da Costa Pinto (1991), on the other hand, reported that articulatory suppression did not eliminate a language difference for Portuguese-English bilinguals and postulated that memory span would be superior in the mother tongue due to greater familiarity with digits in the dominant language.

One explanation for the lack of convergence in these studies could lie in inconsistencies in both the representational form of the stimuli and presentation modalities. Ellis and Hennelly (1980) and da Costa Pinto (1991), for example, measured reading rate using both numerals and digit words, obtained suppressed memory span measures for digit word stimuli, whereas, memory span was estimated in the auditory modality. Chincotta and Hoosain (1995) and Experiment 1, on the other hand, used numeral stimuli for both reading rate and digit span measures with and without articulatory suppression. It was of some interest, therefore, to examine the effects of articulatory suppression on digit representation in the same modality to examine the effects of this procedure more closely.

As far as numeral stimuli are concerned articulatory suppression has consistently been found to eliminate bilingual differences in memory span for three language pairings (Chincotta & Hoosain, 1995; Experiment 1), thus, the predictions for numeral stimuli were relatively straightforward. Larger numeral span in Spanish compared to English was expected and the language difference would be abolished with articulatory suppression. The evidence from bilingual studies measuring suppressed levels of recall for digit word stimuli, however, was less consistent and marred by shortcomings in measuring unsuppressed memory span in the auditory modality and suppressed span measures in the visual modality. Additionally, Ellis and Hennelly (1980) obtained control and suppressed measures of digit span performance from different samples. These methodological idiosyncrasies made predicting the effect of articulatory suppression on bilingual digit word span on the basis of previous studies less straightforward.

Recent findings by Hulme et al. (1991, 1995) have shown that long-term memory factors exert an important influence on working memory capacity. It seemed reasonable to suppose that digit words would be more familiar and, hence, have stronger long-term memory representations in the dominant language than in the less dominant language. It was, therefore, predicted that digit word span would be greater for Spanish relative to English and that articulatory suppression would not eliminate the language difference for these stimuli.

6.3.1: Method

Subjects

Sixteen of the subjects (10 female and 6 male) tested in Experiment 1 were selected at random for participation in the present experiment which was conducted approximately 5 months after Experiment 1. The subjects were paid for participation.

Materials

The materials for the reading time task were identical to those in Experiment 6. For measurement of numeral and digit word span with and without articulatory suppression new sequences of items were constructed. For measurement of memory span with articulatory suppression, four sets of sequences of random numbers, varying from 1 to 9 were constructed as described for Experiment 1. Two sets consisted of numerals and 2 sets comprised digit words in Spanish and English. For measurement of memory span under articulatory suppression, four further sets of sequences were constructed and commenced with sequences of 1 item. For the articulatory suppression sequences, the phrase la-la appeared on the screen 1 second after subjects responded to the READY/PREPARADO prompt by pressing a key on a computer keyboard. The phrase la-la remained on the screen for 3 seconds after which a fixation point appeared on the monitor for 1 second indicating that the item sequence would commence. Once the item sequence was presented a second fixation point (1500 msec) and the legend RECALL/RECUERDA (3 seconds) were displayed.

Procedure

The procedure for the measurement of reading time and memory span was identical to that described for Experiment 6. For the articulatory suppression condition subjects were instructed to commence articulating the suppression phrase at the rate of approximately two phrases per second on appearance of the legend la-la. Throughout testing the experimenter monitored the rate of suppression phrase and prompted subjects to increase or decrease the rate as required to ensure that the rate of articulation was constant. When the item sequence terminated the legend RECALL or RECUERDA indicated that articulation should stop and recall commenced.

Before testing a minimum of two practice trials in the articulatory suppression condition with language of practice counterbalanced were allowed. Practice continued until the experimenter was satisfied that the suppression phrase was articulated at the required rate. The order of presentation for language, item, and control or articulatory suppression tasks was counterbalanced by a Latin square.

6.3.2: Results

Reading Time

The reading times for 200 numerals and digit words in Spanish and English were converted into reading time per item (msec) and are represented in Figure 6.3. These data were subjected to a two-way analysis of variance in which language (Spanish or English) and item (numerals or digit words) were within-subjects factors. This showed a significant effect of language (F, (1,15) = 68.70, $p < .0001$), with a shorter reading time in Spanish than English (means = 312 msec/item and 372 msec/item respectively), and of item (F, (1,15) = 62.74, $p < .0001$), with digit words read faster than numerals (means = 322 msec/item and 362 msec/item respectively).

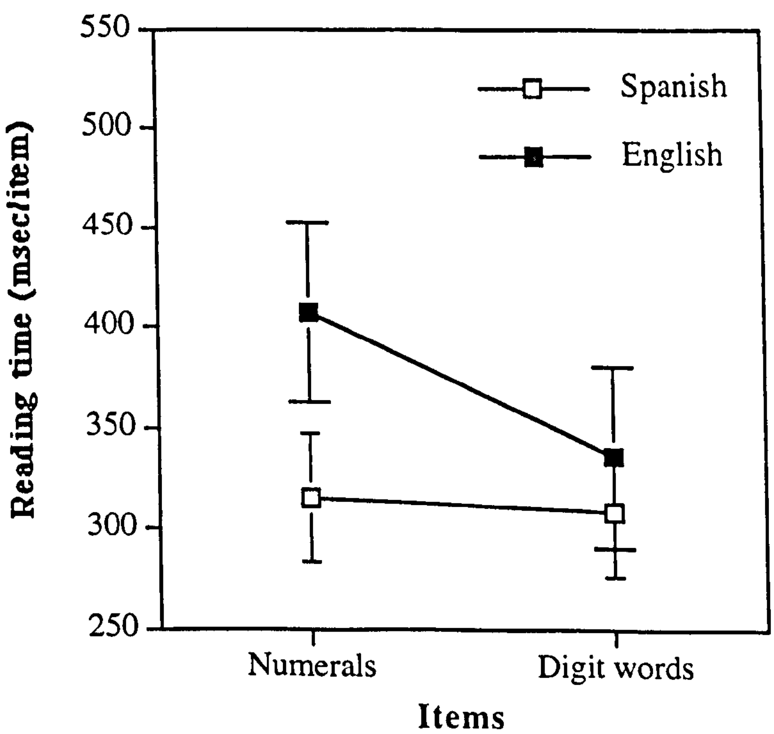

Figure 6.3: Mean reading time (msec/item) in Spanish and English for numerals and digit words.

A reliable interaction between the factors was also present ($F_{(1,15)} = 32.82$, $p < .0001$). Analysis of the interaction by simple main effects indicated between language differences for both numeral ($F_{(1,15)} = 80.79$, $p < .0001$) and digit word stimuli ($F_{(1,15)} = 7.47$, $p < .05$). In both cases Spanish was the language associated with faster reading rate. A difference was also present between numerals and digit words for English ($F_{(1,15)} = 101.31$, $p < .0001$) but not for Spanish. The results of the reading task, then, replicated those of Experiment 6.

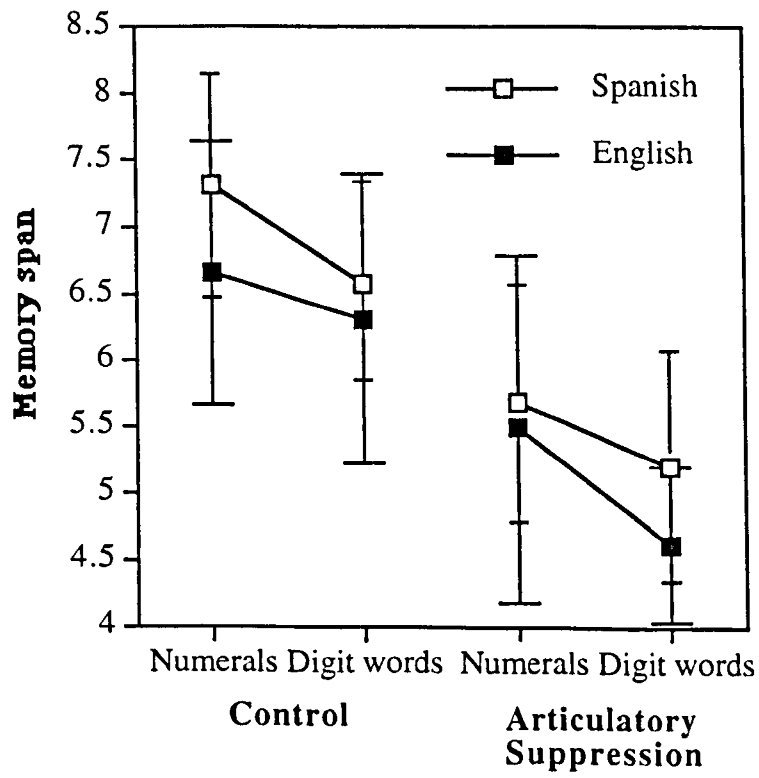

Figure 6.4: Mean control and suppressed memory span in Spanish and English for numerals and digit words.

Digit Span

The data from the digit span tasks were subjected to a three-way analysis of variance in which language (Spanish or English), item (numerals or digit words), and suppression (control and articulatory suppression) were within-subjects factors and are represented in Figure 6.4. This showed a significant effect of language ($F_{(1,15)} = 9{,}99$, $p < .01$), with memory span greater in Spanish than English (means = 6.20 and 5.77

respectively), and of item (F, (1,15) = 31.15, $p < .001$), with memory span for numerals greater than that for digit words (means = 6.29 and 5.69 respectively). The main effect of suppression was also significant (F, (1,15) = 66.17, $p < .0001$, means control = 6.72, suppression = 5.26). None of the two-way interactions between the factors or the three-way interaction (F (1,15) = 2.55) were reliable.

It had been predicted that articulatory suppression would have differential effects on the between-language relationship for numerals and digit words. Although the absence of a higher order interaction indicated that, overall, memory span was larger in Spanish than English a planned analysis revealed that the between-language difference in suppressed memory span for digit words was significant ($t = 3.14$, $p < .01$), whereas the difference between numerals was not.

6.3.3: Discussion

The present findings replicated those of Experiment 6 in that the interaction between the language and item factors observed for the reading rate task was absent for the memory span task. The finding that numeral span was greater than digit word span in both languages and for both suppressed and unsuppressed recall conditions discounted the possibility that translation-based strategies during subvocal rehearsal were responsible for the recall advantage for numerals relative to digit words observed in Experiment 6 when English was the target language

Working memory theory holds that articulatory suppression prevents the translation of visual stimuli into a phonological code by disabling the articulatory rehearsal process thus reducing the contribution of the phonological loop. If bilingual digit span effects are an outcome of differences in the rate of subvocal rehearsal between languages no differences should be observed for either numeral or digit word stimuli under articulatory suppression as recall is determined by processes presumably unaffected by differences in speech rate.

The present results, therefore, suggested that speech rate is not the only determining factor in bilingual memory span as may have been predicted on the basis of phonological loop functioning and raised questions concerning a simple working memory explanation of the bilingual digit span effect. Instead, the view that non-temporal factors contribute to memory span capacity (e.g., Hulme et al., 1991, 1995; Brandimonte, Hitch, & Bishop, 1992) was supported consistent with the arguments expounded in Chapters 2-5.

The paired comparisons indicated discrete effects of articulatory suppression on memory span for numerals and digit words between the languages. Although these results emerged under detailed analysis of a non significant interaction and should not be overplayed, previous bilingual studies have consistently reported the elimination of language differences in numeral span under articulatory suppression (Chincotta & Hoosain, 1995; Experiment 1) and the persistence of language differences under articulatory suppression for digit word stimuli (Da Costa Pinto, 1991; Brown & Hulme, 1992). These findings supported the suggestion that articulatory suppression had discrete effects on numeral and digit word memory span between the languages.

4.4: DISCUSSION OF EXPERIMENTS 6 &7

The present study examined the relationship between speech rate and memory span for numerals and digit words for bilinguals and tested whether reading rate was a reliable predictor of memory span capacity as posited by working memory theory. These Spanish-dominant, Spanish-English bilinguals consistently read digit words faster than numerals in the second language, whereas the distinct number representations were read at equivalent rates in Spanish. A shorter reading time for digit words in English did not predict larger memory spans for numerals than digit words for both Spanish and English.

There existed the possibility that when recall was measured in English, the digit sequences may have been rehearsed covertly in Spanish and translated into the target language at point of recall and that such translation-based strategies would be more efficient for language-neutral numerals than digit words. The results of Experiment 7 confirmed that memory span was larger for numerals than digit words in both languages and for both control and suppressed recall conditions and discounted the possibility that translation-based strategies were responsible for the pattern of results observed in Experiment 6. It was concluded that the factors identified as important determinants of bilingual memory span, namely a numeral advantage over digit words and an advantage of Spanish over English, were not based on processes requiring phonological rehearsal.

The question as to why numerals were advantaged relative to digit words in both languages and for both control and suppressed recall conditions is now addressed. Previous studies have reported a memory span advantage for numerals over a variety of stimuli. Crannell and Parrish (1957), for example, found that memory span was greatest for numerals then letters and then words. Additionally, in an unpublished study, Case (1978, cited in Dempster, 1981) found that numerals were named faster than words and that this difference in item identification predicted larger span for numerals. These studies compared memory span for numerals in relation to arbitrary words rather than digit words and, therefore, do not assist the interpretation of the present findings.

McCloskey, Caramazza, and Basili (1985), however, have demonstrated dramatic differences in processing between numerals and digit words and developed a cognitive architecture of number processing and calculation based on evidence from dissociation studies of brain-damaged patients. This model proposes separate production and comprehension processes for Arabic numbers (numerals) and verbal numbers (digit words). In addition, the processes involved in both comprehension and production for each number representation are mediated by discrete lexical and syntactical components where the former comprises the processing of individual elements in a number (the numeral 1 or the digit word one) and the latter comprises the processing of relationship between the individual numbers when comprehending or producing a multi-digit number (such as 456, or four hundred and fifty-six).

For digit words, an added distinction is made at the lexical processing level between the components required for comprehending or producing spoken (phonological) and written (graphemic) representations. No similar distinction is made at the syntactic level as the processes involved are thought to be the same. Neither are separate phonemic and graphemic components considered necessary for numerals within this cognitive architecture. McCloskey et al. (1985) propose that differences in numeral and digit word processing in normals may occur within the comprehension and/or production subsystems and at the lexical and/or syntactic stages of each subsystem.

In terms of the McCloskey et al. (1985) model it seemed unlikely that the observed difference in numeral and digit word span occurred at the lexical level of the comprehension subsystem as the results of the reading rate task indicated a lack of relationship between naming speed and memory span. Additionally, the memory span task involved the presentation of sequences of single digits which made it unlikely that the syntactic parser of the comprehension subsystem contributed to occasioning the numeral memory span advantage.

Instead it seemed more plausible that the memory span advantage for numerals over digit words occurs within the number production subsystem. If the basic assumptions of the McCloskey et al. (1985) model are correct the Arabic production component is dedicated to processing numerals in written form, whereas the verbal component handles both graphemic and phonological representations of number. Under these circumstances the more specialised system for processing numerals may have been responsible for the more efficient recall of numerals. One possible factor related to greater efficiency in the processing of numerals compared to digit words could lie in differences in the organisation of material for production. Together with Dempster (1981), the view was taken that, a priori, sequences of digits (e.g., telephone numbers, bank accounts, PIN numbers, etc.) are encountered more often as numeral than digit word representations (e.g., 9 5 1 5 2 8 2, as opposed to nine five one five two eight two). This difference in usage between numerals and digit words could occasion more established links between sequences of numerals relative to digit words and this may be the most crucial variable in determining the pattern of memory span.

One explanation of the observed memory span advantage for numeral span, therefore, could lie in that stronger links between the numeral sequences resulted in a greater facility for the recoding of numerals into memorable chunk-like units (Miller, 1956) compared to digit words. An empirical test of this chunking hypothesis could be undertaken by comparing the types of recall errors between numerals and digit words. If numerals are chunked with greater facility than digit words, fewer adjacent transposition and substitution errors for numerals relative to digit words should be present. This pattern of findings would provide partial support for a chunking explanation of the superiority of numeral span over digit word span. Further, for bilinguals the pattern of errors should be equivalent in both languages as the results of Experiment 7 indicated that the language factor did not interact with either the item or suppression factors in the memory span task. An absence of language differences in error patterns would provide additional support for the view that translation-based strategies were not responsible for the effects observed in the present study.

Broadbent and Broadbent (1981) found that articulatory suppression did not disrupt grouping processes in working memory and, thus, concluded that the temporary store in which information is held before grouping is immune to the effects of concurrent articulation and evidence for the view that chunking was not mediated by the phonological loop. Similarly, the notion that the numeral advantage observed in Experiments 6 and 7 was mediated by a relative difference in the predisposition toward grouping or chunking processes for numerals was, thus, consistent with the persistence of the effect under articulatory suppression.

In the Broadbent and Broadbent (1981) study, however, fixed-length sequences of 9 items consisting of digits in one experiment and meaningful (e.g., USA & IBM) and meaningless (e.g., SBU & IMA) trigrams in a second experiment were presented. Moreover, grouping processes were encouraged by increasing the inter-stimulus interval between triplets of items. In the present study, however, the items were presented at a constant rate and this suggested that the hypothesised grouping or processes were engaged independently of temporal cues.

To summarise, the present results converged with a number of recent findings (e.g., Hulme et al., 1991, 1995) that have demonstrated the role of long-term memory representations in determining working memory capacity. The strength of long-term memory representations for language-neutral numerals and language-specific digit words is likely to vary between the second language of the bilingual and may have occasioned differences in the operational efficiency with which the items were processed. In addition, although numerals were recognised and articulated more slowly than digit words in the second language, stronger long-term representations and a hypothesised greater efficiency in organising for the former into more memorable chunk-like units was sufficient to overcome the disadvantage in naming the stimuli observed in the reading rate task.

The present findings, therefore, indicated that the relationship between reading time and memory span was not as straightforward as predicted by a simple version of working memory theory and contributed towards moderating the view that holds speech rate to be the most influential determinant of verbal memory span. As far as accounting for the observed numeral advantage in the memory span tasks was concerned, although previous studies have identified a superiority for numerals over other stimuli in processes involving recognition and memory capacity, questions regarding the nature of this advantage have been left open. It was speculated that a chunking hypothesis could explain this pattern of findings and a paradigm in which this explanation could be tested suggested. Such a study was subsequently undertaken and is presented in Chapter 7.

Chapter 7

Chunking and the Numeral Advantage Effect

In Experiment 6 it was found that for a group of Spanish-dominant Spanish-English bilinguals memory span for Arabic numerals (e.g., 1, 2, & 3) was greater than for digit words (e.g., one, two & three) in the dominant language despite an equivalence in reading time between the items. A numeral advantage was also present when memory span was measured in the less dominant language although, in this case, the reading time measures indicated a slower reading rate for numerals relative to digit words. The possibility that rehearsal may have been undertaken in Spanish when recall was specified in English resulting in a bias in favour of recall for the language-neutral numeral stimuli was excluded by the finding in Experiment 7 that the numeral advantage over digit words persisted for both languages under articulatory suppression. Taken together, these findings indicated the involvement of factors other than subvocal rehearsal in memory in moderating the numeral advantage effect and, thus, raised questions concerning a simple working memory theory explanation of the bilingual digit span effect (Ellis & Hennelly, 1980).

In terms of working memory theory, the memory span advantage for numerals over digit words when performance was specified in the dominant language (Experiments 6 & 7) was perplexing because the speech rate estimates did not predict performance on the memory span tasks. Although several studies (e.g., Crannell and Parrish, 1957; Case, 1978 cited in Dempster, 1981) have reported larger memory spans and faster naming latencies for numerals relative to words, these studies compared performance for numerals in relation to arbitrary words rather than digit words. A comparison between semantically identical items with equivalent articulatory durations (in the dominant language) that varied in the manner of representation had not been examined.

In Chapter 6 it was posited that one influential factor that mediated the numeral advantage effect was the assumed variation in the strength of associative connections between numerals and digit words. It was reasoned that this may have led to a bias in the predisposition toward processing the stimuli into more memorable chunk-like units in favour numerals. This notion was examined further in Experiment 8 using similar Spanish-English bilinguals.

7.1: The Chunking Hypothesis

If it is assumed, a priori, that sequences of digits are encountered more often in numeral than digit word form in print (e.g., 9 5 1 5 2 8 2 as opposed to nine five one five two eight two) it seemed plausible that more established links between numerals relative to digit words was a critical variable affecting the pattern of memory span in Experiments 6 and 7. This suggested that stronger links between numerals may have resulted in a bias in favour of these items towards a greater efficiency in recoding the sequences into chunks (Miller, 1956) compared to digit words. The chunking process, broadly defined, allows information to be recoded economically in terms of processing capacity by integrating discrete items of information into larger units. Consequently, memory span may be increased dramatically by expanding the number of items within each chunk.

Zhang and Simon (1985) have suggested that subvocal rehearsal rate is influenced by chunking, therefore, one explanation of the memory span advantage for numerals over digit words could lie in differences in the relative efficiency with which the items are recoded into chunks and rehearsed prior to recall. Although it was postulated (Chapter 6) that the numeral advantage effect was occasioned by processes related to chunking, it seemed unlikely that in this case the variation in memory span was mediated by a difference in subvocal rehearsal between numerals and digit words as the relationship between these representations of number persisted under articulatory suppression. Instead, the findings of Experiment 7 were consistent with those of Broadbent and Broadbent (1981) which found that the effects of temporal grouping persisted under articulatory suppression. It seemed clear, therefore, that the processes that modulated the numeral advantage effect were independent of subvocal rehearsal. It was reasoned that a variation in the strength of associative connections between the stimuli occasioned a grouping bias in favour of numerals akin to the effect of temporal grouping and that this explained why the numeral advantage effect was resistant to the effects of articulatory suppression.

As detailed in Chapter 6, an empirical test of the chunking hypothesis of the numeral span advantage could be undertaken by comparing the types of recall errors for numerals and digit words. If numerals are recoded into chunks with greater facility than digit words it seems reasonable to suppose that a predisposition towards recoding numerals into chunks should occasion a decrease in order errors in recall. To explain, chunking entails the recoding of individual items (e.g., 7, 5, 3) into a single unit, (i.e., 753), therefore, once discrete items are unitised in this manner recall attempts should, arguably, be more all-or-none when information is chunked than when it is not. In other words, when three individual items are grouped as 753 it is arguably less likely for any of the items within the chunk to be transposed or substituted. If differences in chunking efficiency between the items are present it seemed plausible that fewer transposition and substitution type errors would be present for the unitised numeral chunks relative to digit words.

The chunking hypothesis, therefore, predicted fewer transposition and substitution errors for numerals relative to digit words. Such a finding would be interpreted as an indication of differences in operational efficiency between the stimuli and a further demonstration of the involvement of factors other than subvocal rehearsal in memory span tasks. Moreover, it was suggested in Chapter 6 that for bilinguals an absence of language differences across error types would support the view that translation-based strategies were not responsible for the numeral advantage effect in the less dominant language and indicate that the recall processes between the languages were equivalent.

The experiments presented in Chapter 6, unfortunately, did not allow a test of the chunking hypothesis as no record of errors was maintained. The motivation for this next study was, thus, relatively straightforward. Experiment 7 was replicated and recall error data for numerals and digit words were recorded for Spanish-dominant Spanish-English bilinguals, thus, allowing an empirical test of the chunking hypothesis. In addition, the present study examined the relationship between chunking and familiarity further by including a condition in which unfamiliar representations of digits (modified versions of playing cards were presented. The hypotheses generated by this manipulation as well as the results are reported separately for ease of presentation.

Within the working memory model (e.g., Baddeley, 1990), the functioning of the phonological loop is overseen by a modality-free central executive that monitors attentional resources during information processing and allocates additional storage and processing capacity when the system is overloaded (see, e.g., Baddeley, 1986). In addition, the central executive is thought to play a part in the transformation of information into more efficient codes such as chunks (Baddeley & Hitch, 1974). Secondary tasks such as the random generation of letters (Baddeley, 1986) overload the central executive and disrupt its normal functioning. The requirement of generating random letter strings, thus, elicits a sequenced alphabet schema which conflicts with the requirement of keeping the output sequence random. Under these circumstances the intervention of the central executive is twofold: it assists the selection of strategies involved in the generation of items and simultaneously monitors output to ensure that it is sufficiently random. Random generation tasks are, therefore, a suitable means of interfering with central executive functioning and examining its role within the working memory model (see, e.g., Baddeley, 1996).

According to working memory theory the central executive plays a crucial role in the recoding of information into chunks (Baddeley & Hitch, 1974). In order to assess the involvement of the central executive in memory span tasks for numerals and digit words a random generation condition was introduced into the design. It was reasoned that if the numeral effect is moderated by chunking processes and the central executive is implicated in the reorganisation of material into chunks, the demands of the random generation secondary task would occasion an increase the number of transposition and substitution errors compared to the control and articulatory suppression recall conditions. Moreover, if the numeral advantage effect is moderated by processes that are similar to the effect of temporal grouping, the pattern of errors in the control and articulatory suppression conditions should not differ given the resistance of grouping effects to a concurrent articulation secondary task loading (Broadbent & Broadbent , 1981). Thus, by comparing differences in error types between recall conditions insight would be gained on the relative involvement of the central executive and phonological loop components of working memory in moderating the numeral advantage effect.

7.2: EXPERIMENT 8

7.2.1: Method

Subjects

The subjects were 36 (12 male and 24 female) Spanish dominant, Spanish-English bilinguals attending a British university. Subjects had received schooling in Spanish and had studied English for an average of 9 years. The sample consisted of 20 Arts, 9 Science, and 7 Business and Economics students. The subjects were paid for participation.

Materials

For the measurement of articulation time, a set of digit triads (1-9) was constructed at random with the restriction that each digit occurred once in the set. The triads were varied systematically to make 9 sets of items each consisting of three triads. For the measurement of reading rate the digits from 1 to 9 were randomly varied to construct four lists of 100 items. Two of the printed lists consisted of Arabic numerals (e.g., 1, 2, & 3), the remaining two lists contained digit words (e.g., one, two, & three) in Spanish or English. Consecutive repetition of numbers, as well as ascending or descending sequences of more than two items were avoided. Each list was printed in 10 rows each containing 10 items. Written instructions were prepared in both Spanish and English.

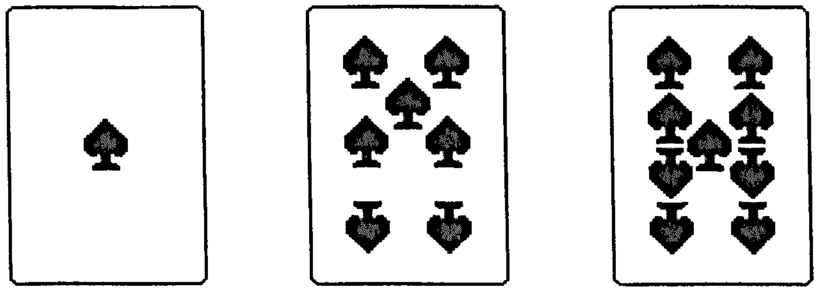

Figure 7.1: Examples of playing card stimuli used as low familiarity representations of number.

For the measurement of memory span, 9 sets of random digit sequences (1-9) were constructed. Identical items appearing contiguously and ascending and descending sequences were avoided. After two sequences of the initial length, the number of items increased by one and so on. For the measurement of memory span for the playing card stimuli, a set of traditional playing cards representing the range from the ace to the nine for the suit of spades were digitised and the Arabic numerals normally present in the top left and bottom right hard corners deleted (examples of the modified playing card stimuli are presented in Figure 7.1). It should be noted that the playing card stimuli were modified from a traditional English deck. Spanish playing cards differ markedly in terms of suits and the configuration of symbols. The present card stimuli were, therefore, considered sufficiently novel to ensure a low level of familiarity for the present bilinguals.

The sequences were presented visually at the rate of one item per second and each successive item appeared in the same position on the monitor. Six sets comprised Arabic numerals, six sets comprised playing cards, and the remaining sets consisted of either Spanish or English digit words. In the control condition the numeral and digit word sequences commenced with a length of three items, whereas in the remaining recall conditions for these stimuli the sequences commenced with a length of one item to prevent possible floor effects. For the playing card stimuli the control condition had an initial sequence length of 2 items and the remaining recall conditions commenced with one item.

The presentation sequence was as follows. First, the legend READY or PREPARADO (the Spanish equivalent) appeared and prompted subjects to press the space bar after which a blank screen appeared for 500 msec, followed by a fixation point (500 msec) and the item sequence. When the item sequence terminated a blank screen appeared for 2 seconds followed by the legend RECALL or RECUERDA which prompted subjects to commence recall.

For the measurement of memory span under articulatory suppression and random generation conditions, the phrase la-la or the legend LETRAS (the Spanish word meaning letters) respectively appeared on the screen 1 second after the sequence was initiated and remained visible for 2 seconds. This prompted subjects to commence articulating the phrase or the random generation of letters respectively. The remaining presentation sequence was as follows, a blank screen (1 second), a fixation point (1 second), a blank screen (500 ms), and the item sequence. Two seconds after the sequence terminated the legend RECALL or RECUERDA appeared and prompted subjects to commence verbal recall.

Thus for all three recall conditions the recall of sequences was prompted 2 seconds after presentation of the last item. For the articulatory suppression and random generation conditions commencement of the secondary task was signalled 4.5 seconds prior to the presentation of the item sequence and ensured that the secondary tasks were started before the item sequences were presented.

Procedure

The subjects were tested individually by a fluent bilingual. First measures of articulation rate in Spanish and English were taken. The experimenter read a digit triad in the target language the subjects memorised the sequence and commenced articulating as fast as possible until instructed to stop. The subjects repeated the digit triad until ten repetitions were counted by the experimenter and the time taken measured by stop watch. Three articulation measures were taken for each language with triad and language counterbalanced by a Latin square. Next measures of reading time for 100 numerals and digit words in Spanish and English were taken. Subjects read the lists as quickly as possible pronouncing each digit individually and audibly and time measured by stopwatch. Prior to the test block subjects practised reading a list of 50 digits. The language of practice and list order were counterbalanced by a Latin square.

Prior to the memory span test block, subjects were familiarised with the playing card stimuli and the salient features of each card representation of a number pointed out. The subjects were taught to identify the digit represented by the playing card without resorting to counting each individual component within the card (i.e., the number of spade tokens contained). Familiarisation with the stimuli was reinforced with an identification task that consisted of the presentation of three randomised sets of card stimuli (total items = 27) on a computer screen to which the subjects responded by pressing the appropriate numerical key on a computer keyboard (the subsequent item was not presented until the correct key was selected).

Next, subjects were shown two examples of a presentation sequence. Subjects were then introduced to the articulatory suppression tasks and practised repeating the phrase "la-la" continuously at the rate of one phrase per second in time to a metronome. Subjects completed two practice memory span trials involving articulatory suppression counterbalanced for language

Subjects were next introduced to the random generation task and asked to imagine a hat containing the 28 letters of the Spanish alphabet from which letters were selected at random, articulated, and replaced. The subjects were reminded that words, acronyms (e.g., NATO or USA), and regular sequences (e.g., A, B, C, & X, Y, Z) would be improbable. Subjects practised the random generation task, generating approximately 20 letters at the rate of one item per second paced by a metronome and completed two practice trials counterbalanced for language. The random generation task was undertaken exclusively in Spanish as it was reasoned that performing the task in English when recall was specified in the same language would place undue additional demands on processing thereby preventing an equivalence of difficulty between tasks.

Finally, memory span for numerals, digit words, and playing cards in Spanish and English under the three recall conditions was measured. Memory span was operationalised as the length of the of the last correctly recalled sequence and recall attempts were recorded both manually and on audio-cassette. If both attempts at the last sequence length were correct a score of 0.5 was added. The order of presentation of trials and the language of instruction and practice were counterbalanced by Latin square. After half the memory span trials subjects were allowed a break of 5 min.

7.2.2: Results

Speech Time

The data from the articulation task were transformed into measures of time per item (msec) and subjected to a one-way analysis of variance in which language was a within-subjects factor. This indicated a difference in articulation time between the languages (F (1,35) = 25.01, $p < .0001$) with faster articulations for Spanish than English (means = 232 msec/item and 260 msec/item respectively).

The data from the reading task were transformed into measures of time per item (msec) and is summarised in Figure 7.2. These data were subjected to a two-way analysis of variance in which item (numerals or digit words) and language (Spanish or English) were within-subjects factors. This revealed reliable main effects of item (F (1,35) = 99.26, $p < .0001$) with numerals read faster than digit words (means = 375 and 329 msec/item respectively) and language (F (1,35) = 165.58, $p < .0001$) with reading time shorter in Spanish than English (means = 321 and 384 msec/item respectively). The interaction between the factors was also reliable (F (1,35) = 112.57, $p < .0001$).

Analysis of the interaction by simple main effects indicated a shorter reading rate in Spanish than English for both numerals (F (1,35) = 238.71, $p < .0001$, means = 322 and 429 msec/item respectively) and digit words (F (1,35) = 7.55, $p < .01$, means = 320 and 339 msec/item respectively). Digit words were read faster than numerals for English (F (1,35) = 165.58, $p < .0001$) but no difference between the items was present for Spanish, and hence the interaction term.

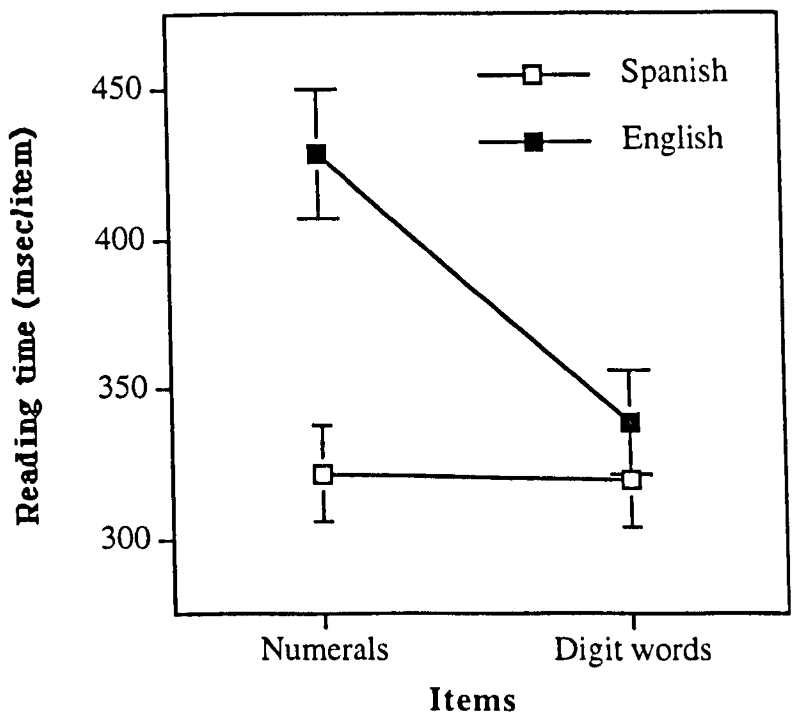

Figure 7.2: Mean reading time (msec/item) in Spanish and English for numerals and digit words.

In summary, the results of the speech tasks indicated that articulation time and reading time were faster in Spanish than English. Item representation had a effect on reading rate when this was measured in English but not Spanish. These results, therefore, replicated the findings of Experiments 6 & 7.

7.2.3: Numerals and Digit Words

Memory Span

The numeral and digit word stimuli were analysed separately to the playing card stimuli in order to replicate the studies described in Chapter 6 as closely as possible. The numeral and digit word memory span data were subjected to a three-way analysis of variance in which language (Spanish or English), recall condition (control, articulatory suppression, or random generation), and item (numerals or digit words) were within-subjects factors and is summarised in Figure 7.3. This revealed reliable main effects of language (F (1,35) = 11.05, $p < .01$) with a larger memory span for Spanish than English (means = 4.86 and 4.57 respectively), and item (F (1,35) = 11.47, $p < .01$) with larger memory span for numerals than digit words (means = 4.86 and 4.56 respectively). The main effect of condition upon recall was also reliable (F (2,70) = 379.20, $p < .0001$) with larger spans under control conditions then articulatory suppression and then random generation (means = 6.22, 5.01, and 2.90 respectively). Further analysis by t-test revealed that all the comparisons between recall conditions were reliable (all $p < .01$). The two-way interaction between language and item was reliable (F (1,35) = 10.88, $p < .01$). The higher-order interaction was not reliable (F (2,70) < 1).

Analysis of the interaction between language and item by simple main effects indicated that memory span for Spanish was greater than English for digit words (F (1,35) = 16.80, $p < .001$) (means = 4..82 and 4.31 respectively) but not for numerals. Numeral span was greater than digit word span for English (F (1,35) = 16.98, $p < .001$, means = 4.82 and 4.31) but not for Spanish, and hence the interaction term.

To summarise, although the main effects of language and item indicated an overall larger memory span for Spanish than English and an advantage for numerals over digit words the interaction between the factors indicated that no between-item difference for Spanish and no between-language difference for numerals were present. These findings were unexpected in that they provided only partial support for the numeral advantage observed in Experiments 6 & 7 although for the control and articulatory suppression conditions the relationship between the conditions was in the right direction and tended toward a larger span for numerals than digit words. Inspection of the means suggested that the absence of a numeral advantage over digit words for Spanish may have been partly due to a reversal of the effect in the random generation task.

The results of the reading task indicated that numeral and digit word reading time were equivalent in Spanish, whereas reading time for digit words was shorter than for numerals in English. Thus, although reading time predicted performance on the memory span task for Spanish, it did not predict the superior recall for numerals in English.

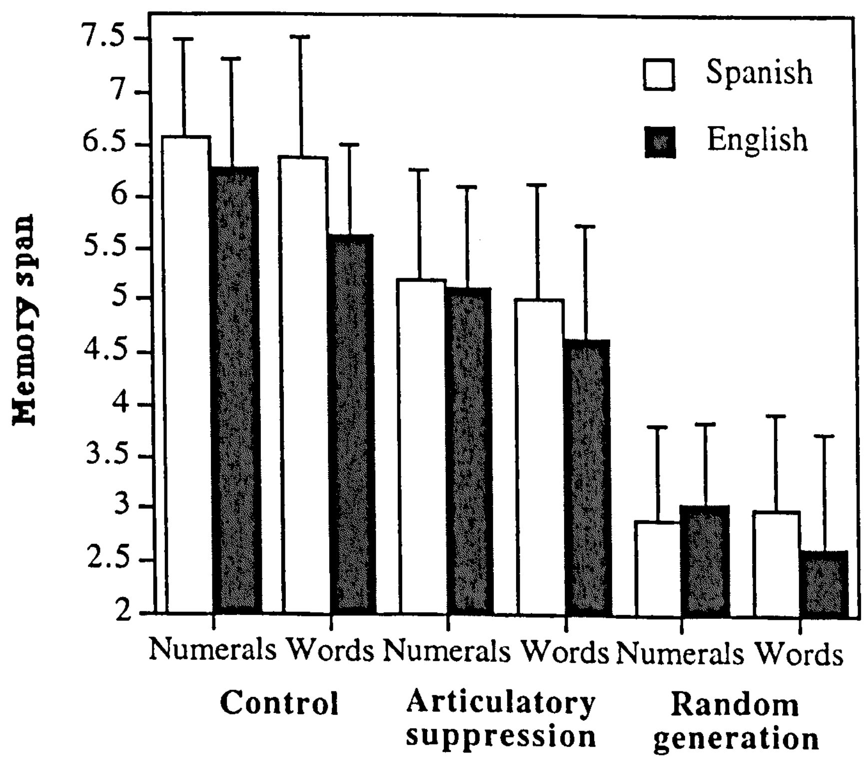

Figure 7.3: Mean memory span for numerals and digit words in Spanish and English for three recall conditions.

Errors Analysis

Each subject's recall attempt subsequent to the last correctly recalled sequence was analysed and the errors classified according to the following criteria. An addition error was recorded for each item in the recall response that exceeded the number of items contained in the presentation sequence. When the number of items in the recall response contained items that were not presented a substitution error was noted for each replaced item. A transposition error was noted for each item recalled in an incorrect serial position. Finally, when a recall attempt omitted items without an attempt at replacement a deletion error was noted. The responses were analysed for each subject and for each condition varied in terms of the number of items in the presentation sequence. This variation in sequence length was equated by expressing the number of errors in each category as a ratio of the number of items in the attempted presentation sequence.

The error data were subjected to a four-way analysis of variance in which item (numerals or digit words), language (Spanish or English), recall (control, articulatory suppression, or random generation), and error type (addition, transposition, deletion or substitution) were all within-subject factors. The results indicated a main effect of recall (F (2,70) = 24.22, $p < .0001$) with less errors per digit in the control condition, then suppression then random generation (means = .113, .123 and .160 errors/digit respectively). Further analysis by t-test indicated differences in the number of errors between the random generation and control (t = 6.61, $p < .01$) and random generation articulatory suppression (t = 5.20, $p < .01$) conditions of the recall factor. The main effect of error type was reliable (F (3,105) = 177.33, $p < .0001$) with more transposition errors (.304), then substitutions (.111), then deletions (.092), and then additions (.006). Further analysis by t-test revealed that all comparisons, bar that between deletions and substitutions, were reliable (all $p < .01$).

The two-way interaction between recall and error type was reliable (F (6,210) = 8.44, $p < .0001$) and the two-way interaction between item and error type was marginal (F (3,105) = 2.48, $p = .065$). The higher order interaction was not reliable F (6,210) < 1). No main or interaction effects were associated with the language factor; a finding that indicated an equivalence in the frequency and type of errors made for Spanish and English.

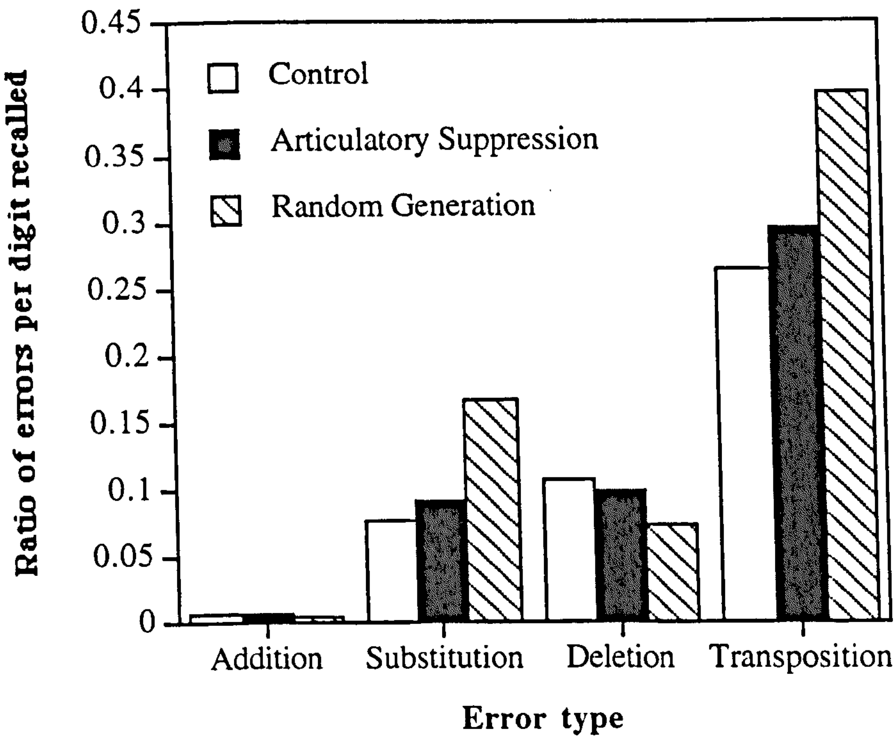

Figure 7.4: Mean ratio of errors per digit recalled for three recall conditions as a function of error type.

The interaction between recall and error type was analysed by simple main effects and is summarised in Figure 7.4. This indicated differences in the number of transposition (F (2,70) = 46.94, $p < .0001$), and substitution (F (2,70) = 22.83, $p < .0001$) errors in each recall condition. Further analysis by t test indicated that in the case of transposition errors the differences between recall conditions were all reliable ($p < .05$). At the substitution error level more errors were made under random generation relative to the control and suppression conditions ($p < .01$) which did not differ between themselves. These results indicated that random generation selectively occasioned more transposition and substitution errors but not addition or deletion errors relative to the control and articulatory suppression conditions. The selectivity of the random generation condition in occasioning a greater proportion of transposition and substitution errors suggested that the effect of this secondary task could not be simply attributed to hypothesised greater cognitive demands for this task compared to articulatory suppression. The finding that disrupting central executive functioning resulted in an increase in ordering errors indicated that this component of working memory is involved in the organisation of material in readiness for recall as predicted by the working memory model.

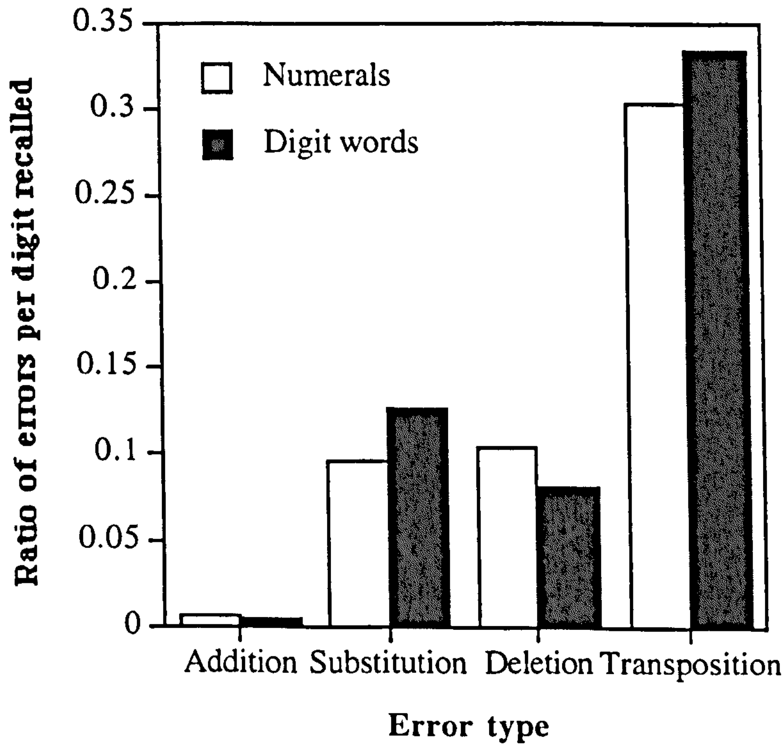

Figure 7.5: Mean ratio of errors per digit recalled for numerals and digit words.

The analysis of the interaction between items and error type by simple main effects is summarised in Figure 7.5. This indicated differences in error type for both numerals (F (3,105) = 79.08, $p < .0001$) and digit words (F (3,105) = 99.90, $p < .0001$). Further analysis by t-test revealed that for both numeral and digit word stimuli all the differences between error types were reliable at the $p < .01$ level with the exception of comparisons between deletion and substitution errors. Here the difference between these error types was reliable at the $p < .05$ level for digit word stimuli and no difference was present for numeral stimuli. Analysis of the difference between numerals and digit words for each error type indicated differences at the transposition (F (1,35) = 5.84, $p < .05$, means = .304 and .334 respectively) and substitution (F (1,35) = 5.61, $p < .05$, means = .096 and .126 respectively) error type levels. Thus, these results indicated that more transposition and substitution errors were made for digit words than numerals: a finding in keeping with the chunking hypothesis that predicted fewer order errors for the numeral stimuli.

To summarise, the results of the errors analysis indicated that no differences were present between the languages and supported the view that the underlying recall processes between the languages were equivalent. The interaction between error type and recall condition indicated that the random generation secondary task produced more transposition and substitution errors relative to the control and articulatory suppression condition. A difference in the frequency of transposition errors was present between the control and suppression condition but this did not interact with digit representation. The differences in the number of transposition and substitution errors between numerals and digit words indicated processing differences between the representations of number in accordance with predictions made by the chunking hypothesis

When reading time was measured in the dominant language number representation was of no consequence, whereas in the less dominant language digit words were read at a faster rate than numerals. The results of the reading task, thus, replicated the interaction between language and number representation reported in Chapter 6.

With regard to the memory span task, the present findings partially replicated those of Experiment 7 in which an advantage for numerals over digit words was present, however, this was limited to the conditions where performance was specified in the less dominant language. The present findings indicated that despite a shorter reading time for digit words than numerals in the less dominant language the present bilinguals obtained larger memory spans for numerals than digit words: a relationship that persisted under the articulatory suppression and random generation secondary tasks. This finding supported the notion that the relationship between reading rate and memory span was not as straightforward as suggested by a simple working memory and indicated the involvement of factors other than subvocal rehearsal.

7.2.4: Discussion

The motivation for obtaining memory span data for numerals and digit words under the three recall conditions, however, was to collect of data with which to examine the differences in recall errors between the stimuli proposed by the chunking hypothesis described in Chapter 6. The results of the error analysis indicated that more transposition and substitution errors were made for digit words relative to numerals and that the random generation secondary task selectively occasioned more order errors relative to the remaining recall conditions. Furthermore, the finding that no language differences were present between error types supported the suggestion that the information was processed equivalently in Spanish and English and discounted the possibility that the superior span for language-neutral numeral stimuli in the less dominant language was a result of translation-based strategies.

Although articulatory suppression occasioned more transposition errors relative to the control condition, it did not abolish the numeral advantage effect. Moreover, the error type factor did not interact with digit representation. The prevention of subvocal rehearsal, thus, resulted in an equivalent increase in transposition errors for both numerals and digit words relative to the control condition. This finding supported the view that the numeral advantage effect was not mediated by phonological loop functioning. The finding that one of the consequences of articulatory suppression was an increase in the tendency to make transposition errors but not substitution errors suggested that one role of subvocal rehearsal is memory span tasks is to maintain the order of items in readiness for recall. This was in contrast to the findings of Broadbent and Broadbent (1981) in which the effects of temporal grouping were unaffected by articulatory suppression. One crucial difference between the studies, of course, was that Broadbent and Broadbent (1981) induced a grouping pattern by increasing the inter-stimulus interval between triplets of digits, whereas in the present study the rate of presentation was constant. In addition, Broadbent and Broadbent (1981) used a fixed length of 9 digits in their study and this may have increased the level of support during recall. An explanation for the variation between these studies is that the consequences of articulatory suppression on the disruption of grouping effects could depend crucially upon whether the grouping patterns are made explicit and supported by the rate of presentation and the nature of the recall task.

Overall, the analysis of the numeral and digit word data supported the suggestion that a greater efficiency in recoding numerals into chunk-like units relative to digit words was an influential factor in determining differential memory spans between the items.

7.2.5: Playing Cards

The relationship between digit representation and chunking was examined further by including a condition in which less familiar representations of number in the form of modified versions of playing cards were presented (Figure 7.1). This manipulation equated the degree of familiarity with number representation between the languages and allowed a test of two separate hypotheses.

First, if the predisposition to unitise information into chunks was related to the level of familiarity with the stimulus, playing card stimuli would be chunked in a relatively less efficient way than numerals or digit words. An analysis of recall errors should therefore reveal that, in this case, a random generation task would not occasion more transposition or substitution errors relative to the control or articulatory suppression conditions.

Second, there is some evidence that factors other than subvocal rehearsal are influential determinants of the bilingual digit span effect. The findings of Experiment 1, for example, demonstrated that the language in which bilinguals received schooling was an important variable affecting digit span, as was the manner in which digits were represented. Furthermore, it was demonstrated in Experiment 2 that the power of speech rate in predicting bilingual digit span varied depending upon how this is estimated.

For the playing card stimuli, then, the discrete levels of familiarity considered to occasion a performance bias in favour of the more dominant language (particularly for language-neutral numeral stimuli) in visual digit span tasks were equated by the use of unfamiliar number representations. Consequently, the chunking and familiarity factors should be less influential determinants of a memory span which, under these conditions, should theoretically be mediated more or less exclusively by the speed of recognition and subvocal rehearsal. It was predicted that the speech rate estimates would indicate consistently faster performance in Spanish than English and, therefore, memory span for playing cards was expected to be larger in Spanish than English under control conditions.

The low level of familiarity with the playing card stimuli made it less likely that chunking processes were influential determinants of memory span performance for these stimuli. Moreover, the subjects were given training and practice in identifying the playing cards in a manner that made it unnecessary to count the individual components constituting the playing card in order to identify which digit was represented. Performance in the playing card memory span task was, therefore, likely to be mediated by the speed of recognition and the rate of subvocal rehearsal but not differences in familiarity (or the strength of long-term representation) between the languages.
It was predicted that articulation time would be shorter in Spanish than English, therefore, memory span for playing cards was expected to be larger in Spanish than English under control conditions. In addition, if articulatory suppression removed the language difference in memory span under control conditions, this would support the view that the difference in the speed of recognition of the digits represented by the playing cards between Spanish and English was not an influential determinant of performance under these conditions.

Memory Span

The memory span data for the playing card stimuli were subjected to a two-way analysis of variance in which language (Spanish or English) and recall condition (control, articulatory suppression, or random generation) were within-subjects factors and is summarised in Figure 7. 6. This showed a main effect of language (F, (1,35) =

22.18, $p < .0001$) with larger memory span for Spanish (4.43) than English (4.00) and recall condition (F, (2,70) = 22.18, $p < .0001$) with larger memory span under control conditions (5.43) then articulatory suppression (4.60), and then random generation (2.62). Further analysis by t-test revealed that all comparisons between recall conditions were reliable ($p < .001$).

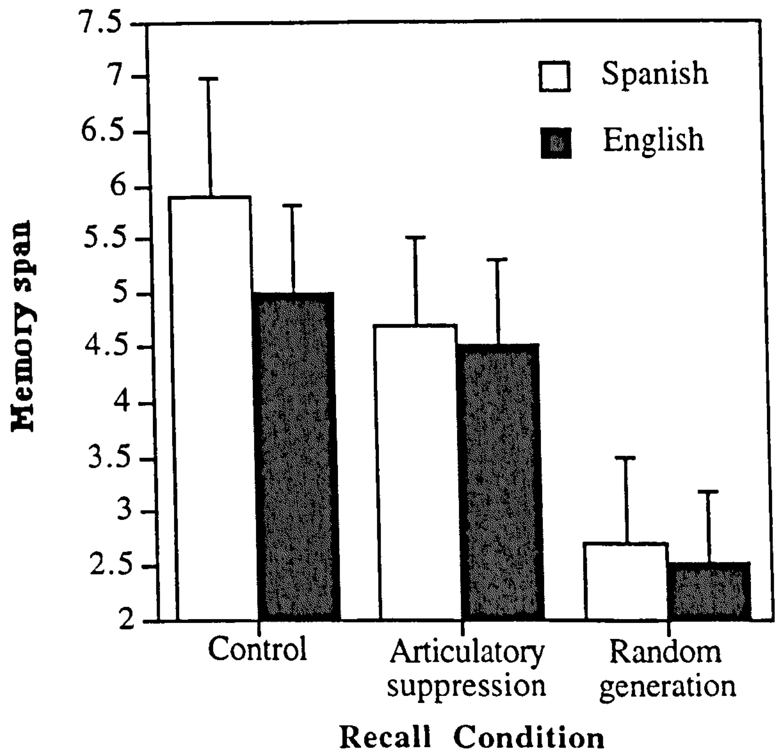

Figure 7.6: Mean memory span for the playing card stimuli in Spanish and English under three recall conditions.

The interaction between the factors was also reliable (F, (2,70) = 22.18, $p < .0001$). Analysis by simple main effects indicated that differences were present across recall conditions for both Spanish (F, (1,35 = 121.36, $p < .0001$) and English (F, (1,35 = 80.65, $p < .0001$). Further analysis by t-test indicated that the within-language comparisons across recall conditions were reliable to the $p < .001$ level with the exception of the difference between the control and articulatory suppression recall condition for Spanish where $p < .05$. A between-language difference was present for the control level of recall (F, (1,35 = 33.65, $p < .0001$) but not for articulatory suppression or random generation and hence the interaction term. These results, thus, indicated that the language difference present in the control conditions was eliminated by both secondary tasks.

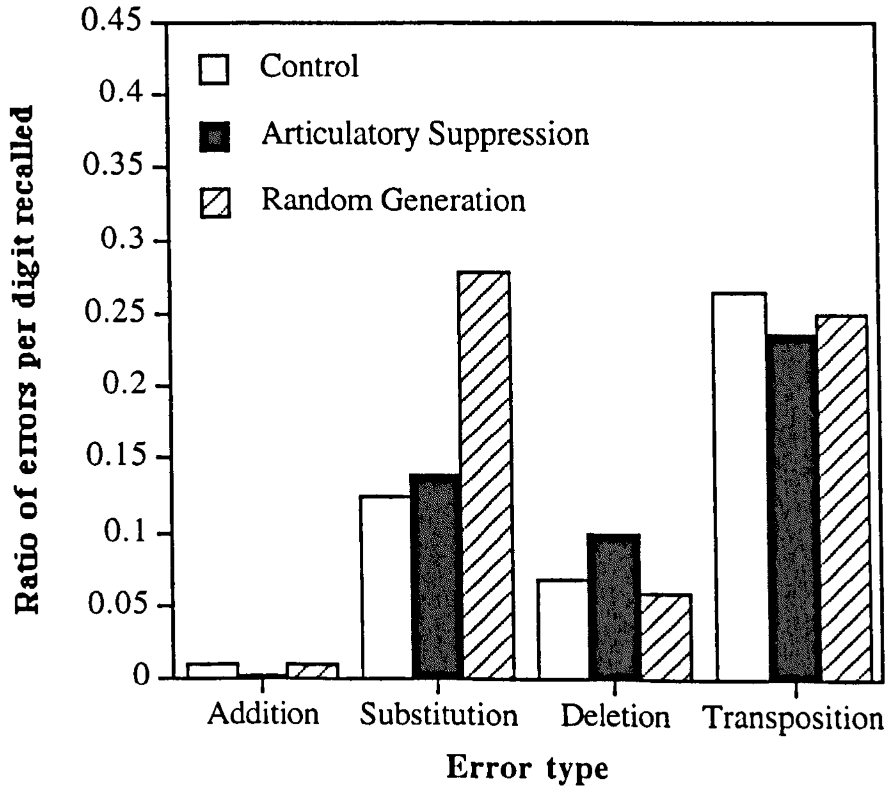

Figure 7.7: Mean ratio of errors per digit recalled for three recall conditions as a function of error type for the playing card stimuli.

Errors Analysis

The error data were classified and transformed as described previously and subjected to a three-way analysis of variance in which language (Spanish or English), recall condition (control, articulatory suppression, or random generation) and error type (addition, transposition, substitution, or deletion) were all within-subjects factors and is summarised in Figure 7.7. The results indicated a main effect of recall condition (F, (2,70) = 7.21, $p < .01$) with less errors per digit recalled under the control condition (.117), then articulatory suppression (.119), and then random generation (.150). Analysis by t-test indicated that more errors were made under the random generation task compared to the control and articulatory suppression conditions ($p < .01$) which did not differ between them. A main effect of error type was present (F, (3,105 70) = 22.18, $p < .0001$) with more transposition errors (.251), then substitution (.181) then deletion (.076), and then addition (.007). Analysis by t-test indicated that all the differences between error types were reliable ($p < .01$).

The two-way interaction between recall condition and error type was reliable (F, (6,210) = 4.18, $p < .001$) but the higher-order interaction was not ($F < 1$). Analysis of the interaction between recall and error type by simple main effects revealed differences in errors across all three recall conditions (all $p < .0001$). A difference was present between recall conditions only at the substitution error type level (F, (2,70) = 39.63, $p < .0001$). Further analysis by t-test indicated that, at this level, more errors were made under random generation (.279) that the control (.124) and articulatory suppression (.139) recall conditions (both $p < .01$) which did not differ between themselves.

To summarise, articulatory suppression abolished the language difference present in the control condition. This finding indicated that the superior memory span for Spanish observed under the control condition was mediated by differences in the rate of subvocal rehearsal. The error analysis revealed that no difference was present in the number of transposition errors made across recall conditions, whereas the random generation task occasioned more substitution errors than controls and under articulatory suppression which did not differ between them. The finding that no main or interaction effects were associated with language in the error analysis suggested that the processing of the material was equivalent between Spanish and English.

7.2.6: Discussion

When the level of familiarity with the material was low, no evidence of chunking as quantified by an equivalence in the frequency of transposition and substitution errors across the three recall conditions was expected. The logic behind this prediction lay in the assumption that random generation, a procedure that disrupts central executive functioning, would not occasion a higher frequency of order errors as chunking processes would not feature as an important factor for the unfamiliar card stimuli.

The present results supported the prediction in terms of transposition but not substitution errors where random generation was, unexpectedly, associated with a higher frequency of errors compared to the control and suppression conditions. One explanation of this finding could lie in the nature of the card stimuli. The use of unfamiliar representations of number made it unlikely that long-term representations would be an important factor in the memory span task, however, it was possible that the card stimuli made heavy demands on the cognitive resources required for the transcoding the visual information into storage codes. Under these circumstances disruption of the central executive by the random generation tasks may have consumed the resources required for the transcoding process and thereby occasioned a decrease in the accuracy of item identification. Consequently, an increase in the frequency of substitution errors was observed.

If this explanation was correct it suggested that the central executive makes a multi-faceted contribution to information processing. That is, it seemed plausible that overloading the central executive independently disrupted the transcoding of visual material into mental storage codes (possibly visual ones) in addition to preventing the use of long-term memory representations necessary for chunking. This notion was consistent with the view that it may be possible to fractionate central executive processes in order to establish whether it is a unitary system or a group of autonomous processes (Baddeley, 1996).

A second hypothesis examined whether articulatory suppression would abolish the predicted language difference in memory span under control conditions. It was predicted that when the levels of familiarity between number representations was equated, recall would be mediated by differences in the rate of subvocal rehearsal. This notion was supported by the finding that articulatory suppression eliminated the superior Spanish memory span present in the control condition. This suggested that it was unlikely that a bias in favour of faster speed of processing and recognition was responsible for the larger memory span for playing cards in the dominant language.

The language difference in memory span present in the control condition was also eliminated by the random generation task: a finding that suggested that the random generation task may have interfered with normal phonological loop functioning in addition to disrupting the central executive. The difference in the frequency of substitution errors between the secondary tasks suggested that each task had discrete effects on memory span for playing cards. However, there may have been a degree of overlap in the disruptive consequences of articulatory suppression and random generation on normal phonological loop functioning. For, although the cognitive demands for each secondary task were quite different the tasks were similar in that they both required overt articulation. Under these circumstances it was, perhaps, unsurprising that the random generation task also abolished the language differential present in the control condition.

7.3: GENERAL DISCUSSION

The motivation for the present experiment was to test the chunking hypothesis explanation of the advantage of numerals over digit words in immediate memory recall tasks put forward in Chapter 6. To do this Experiment 7 was replicated and the recall errors recorded: an analysis of which revealed that a higher frequency of transposition and substitution errors was present for digit words relative to numerals. This pattern of findings was interpreted as indicating discrete levels of chunking efficiency between the stimuli mediated by differences in usage and supported the chunking explanation of the numeral advantage in digit span tasks proposed in Chapter 6. It should be noted, however, that the present results did not exclude the likelihood that digit words were also chunked: the only claim here is that these items are simply chunked in a less efficient manner than numerals.

Qualitative and quantitative differences in recall errors were present across recall conditions. The main finding in this respect was that the random generation secondary task selectively occasioned a greater number of transposition and substitution errors compared to the remaining recall conditions. Random generation tasks overload the central executive and therefore the increase in order errors present for this secondary task indicated the involvement of this component of working memory in the chunking process as suggested by Baddeley and Hitch (1974).

The inclusion of playing card representations of number equated the differences in familiarity for number representations between the languages. It was predicted that chunking would not feature as an important factor in the processing of these novel representations of number as the low level of familiarity with the stimuli would diminish the predisposition to unitise the information into chunks. Consequently, an equivalent frequency of transpositions and substitution errors across recall conditions was expected. The results, however, indicated that random generation occasioned a higher frequency of errors compared to the remaining recall conditions and suggested the involvement of the central executive component in the transcoding of visual information into phonological codes.

The memory span difference between Spanish and English observed under control conditions and predicted by the speech rate estimates was eliminated with an articulatory suppression secondary task. This was some indication that, ceterus paribus, the rate of subvocal rehearsal was a highly influential determinant of memory span as under these circumstances the speech rate measures were a reliable predictor of memory span. This finding further supported the notion that articulatory suppression eliminates the bilingual digit span effect only when comparable levels of fluency between the languages are attained (Chincotta & Hoosain, 1995).

The finding that no language difference was present in the type and frequency of errors indicated that the material was processed in equivalent ways between the language and excluded the possibility that translation-based strategies may have been present when recall was specified in the less dominant language. These findings indicated that the language difference in memory span observed for the control condition was likely to be a consequence of the differential rates of speech between the dominant and less dominant languages of the present bilinguals.

In short, for the number and digit word stimuli the random generation task selectively induced more transposition and substitution errors than the control or articulatory suppression conditions. This pattern of results was interpreted as support for the suggestion that random generation disrupted organisational processes for familiar material. For the playing card stimuli, however, differences in the frequency of transposition errors between recall conditions were not present and indicated that implicit organisational strategies were of no consequence in the processing of unfamiliar representations of number. The higher frequency of substitution errors under random generation compared to the remaining recall conditions was interpreted as evidence for a central executive role in the transcoding of non-verbal, visual information into phonological codes.

Taken together, the present findings indicated important differences in the processing of digits as a function of representation and the level of familiarity with the stimuli. The finding that intrinsic differences in the type of errors made between numerals and digit words provided some support for the notion that attributed the numeral advantage effect to a difference in the predisposition toward some, as yet unspecified, form of chunking between numerals and digit words.

Finally, it was noted that although random generation occasioned more transposition and substitution errors for the numeral and digit word stimuli, the relationship between memory span for numerals and digit words when recall was specified in English remained unchanged. That is, numeral span continued to be greater than digit word span even under random generation. Therefore, although differences in chunkability were present between numerals and digit words the disruption of the central executive was not sufficient to eliminate the difference between the stimuli. This suggested that the numeral effect was not exclusively mediated by differences in chunking predisposition between numerals and digit words: a notion that was examined further in the following chapter.

Chapter 8

Item Identification and the Numeral Advantage Effect

The experiments presented in Chapter 6 indicated that for a group of Spanish-English bilinguals, memory span was greater for numerals (e.g., 1, 2, & 3) than for digit words (e.g., one, two, & three): a pattern that persisted in both languages and when subvocal rehearsal was prevented. Moreover, the estimates of speech rate based on reading time indicated that when performance was specified in the dominant language (Spanish) number representation was of no consequence, whereas for English reading time for digit words was faster than for numerals. These findings were, thus, an exception to the otherwise generally robust relationship between the articulatory duration of items and memory span capacity (Baddeley, Thomson, & Buchanan, 1975) and indicated the presence of non-phonological factors in mediating the bilingual digit span effect.

The notion that the numeral advantage effect was mediated by a variation in the strength of associative links between numerals and digit words resulting in a bias in favour of a predisposition toward chunking for the former representations of digits was examined in Experiment 8. The results were broadly consistent with the chunking explanation of the numeral advantage effect in that more order errors were present for numerals than digit words and that a random generation task selectively induced a greater number of these errors than the control and articulatory suppression condition. Moreover, when the level of familiarity with the representations of digit between the languages was equated with the use of playing card stimuli, random generation did not occasion a higher number of transposition errors relative to the remaining recall conditions.

As was discussed in Chapter 7, however, the finding that a random generation secondary task did not eliminate the numeral advantage effect when performance was specified in English raised the question as to whether the effect was exclusively mediated by chunking processes. For if this were the case, the numeral advantage effect should not have persisted under conditions where the central executive was disrupted (Baddeley & Hitch, 1974). It was reasoned, therefore, that the larger memory span for numerals relative to digit words was moderated additionally by factors that were independent of both subvocal rehearsal and chunking processes. The present study examined the role of non-verbal factors (item identification and speed of perceptual processing) in mediating the memory span advantage for numerals over digit words.

8.1: Item Identification and Speed of Perceptual Processing

Dempster (1981) proposed that item identification is the major source of individual differences in memory span and that the word length effect may be accounted for in terms of variation in item identification with faster response latencies for short words than long words. Similarly, Mackworth (1963) demonstrated that naming speed predicted the memory span relationship between numerals, words and pictures: with a larger span for the items with faster naming latencies. Moreover, Kail (1992) has argued that processing speed makes an independent contribution to articulation rate which, in turn, determines memory span.

Taken together, these findings strongly suggested that variation in the speed with which numerals and digit words are identified might be an important variable in mediating the differential memory span for these items. When the availability of processing time is dependent upon the temporal constraints imposed by limited presentation time, as in memory span tasks, the relationship between identification time and recall performance is likely to be of some consequence. It seemed reasonable, therefore, to expect item identification time to be related to the availability of cognitive resources for the processing of information with a faster response latency allowing more capacity for the encoding and organisation of material prior to recall.

In a comparison of four estimates of cognitive processing in relation to visual memory span, Hitch, Halliday, and Littler (1989) found that articulation time and reading time were equivalently correlated with memory span, whereas auditory and visual response latencies were correlated with suppressed memory span. Interestingly, reading time, but not articulation time, was correlated with suppressed memory span, although the degree of association between this predictor and visual item identification was different. Hitch et al. (1989), thus, concluded that reading time was relatively unaffected by factors related to item identification.

The findings of Experiment 2, however, suggested that when bilingual information processing is examined it is likely that measures of speech time between dominant and less dominant languages are affected by processes related to item identification. This likelihood is increased when the stimuli are language neutral as was demonstrated in Experiment 5 where the eye movements of two groups of Finnish-Swedish bilinguals with different mother tongues were measured during the processing of numerals. The findings suggested that additional demands independent of articulation duration were made when the processing of numerals was specified in the less dominant language. It was, therefore, posited that the absence of lexical support in numerals produced estimates of word length that were contaminated by factors that are relatively insensitive to actual language differences in the spoken duration of digits. It was, thus, concluded that the numeral reading task could plausibly index the relative level of fluency between the languages rather than actual differences in word length as had been previously supposed (Ellis & Hennelly, 1980; da Costa Pinto, 1991; Chincotta & Hoosain, 1995).

Although it was reasonable to suggest that language-neutral representations of digits were prone to Stroop-type interference from the more proficient language when the task is performed in the less proficient one, the question remained as to why the numeral advantage in memory span tasks persisted in the less dominant language despite the assumed heavier processing load. One plausible explanation is that when performance was specified in the less dominant language, the numeral stimuli were in some respects easier to encode and translate into the target language at the point of recall than language specific digit words. While this explanation accounted for performance in the less-dominant language, it did not, however, account for the pattern of results in the dominant language; where the numeral advantage effect was also present. It was argued, moreover, that explicit instructions to conduct rehearsal in the specified language and to commence recall immediately when prompted and to continue without pausing reduced the opportunity for translation-based strategies.

Given the above-cited evidence concerning the role of speed of item identification in mediating memory performance in monolinguals, it was reasoned that similar factors might impinge upon the variation between the languages in bilinguals. The present study, therefore, examined the relationship between the speed of perceptual processing, speech rate and immediate recall for distinct representations of number. Memory span performance for numerals and digit words was measured under silent, articulatory suppression, and random generation recall conditions for a group of Greek-English bilinguals. The main interest of this study, therefore was focused on the power of an item identification task in predicting the relationship between the distinct representations of number in relation to within-language performance.

When bilinguals are required to process language-neutral stimuli, particular care is required to ensure that the material is processed in the target language. The present interest in examining the relationship between item identification latency and memory performance under circumstances that prevented subvocal rehearsal and central executive functioning required a measure of item identification that did not require the activation of articulatory output gestures. To meet these criteria, item identification latency was measured with a cross-modal matching task in which the auditory presentation of a digit in either Greek or English was followed by the visual presentation of a numeral or digit word. The subjects were required to decide whether the item pairs were the same or different in terms of the digits represented by the stimuli. The cross-modal matching task, thus, met the requirement of ensuring that performance was undertaken in the target language (as specified by the auditory stimulus) and that the measures of item identification were independent of vocalization.

The predictions concerning the relationship between the estimates of speech rate, item identification, and memory span were based on the findings of Hitch et al. (1989). Namely, correlations between the speech-based estimates of subvocal rehearsal rate (articulation time and reading time) and control memory span, and reading time and suppressed memory span were expected. Moreover, it was anticipated that item identification latency would be correlated with memory span under articulatory suppression but not under control conditions. Hitch et al. (1989) suggested that reading time is relatively unaffected by factors related to item identification, therefore, although both of these measures would be correlated with suppressed memory span the measures should differ in the degree of association.

Insofar as the reading task was concerned, the present bilinguals were expected to follow the pattern of performance of those in Experiments 5 - 7. That is, when performance was specified in the dominant language (Greek) reading time for numerals and digit words was expected to be equivalent, whereas for English reading time would be slower for numerals than digit words. The crucial question under investigation, however, was whether the item identification measures would predict memory span performance under circumstances in which the central executive component of working memory was disrupted by a random generation secondary task. Such a finding would indicate that item identification made a contribution to mediating the numeral advantage effect independent of processes related to chunking and central executive functioning.

8.2: EXPERIMENT 9

8.2.1: Method

Subjects

The subjects were 24 (11 female, 13 male) Greek-dominant, Greek-English bilinguals attending a British university. All the subjects had attended Greek-medium schools and had studied English for approximately 11 years. The subjects were paid for participation in the experiment.

Design & Procedure

Item identification

For the item identification task a total of 144 digit pairs were constructed with half the pairs (72) allocated to either a Greek or English language block. For each language half the digit pairs (36) were constructed at random subject to the following restrictions. Each digit occurred 8 times (four times in the first position of the digit pair and four times in the second) and the items in the each pair were incongruent. The remaining 36 digit pairs in each language block consisted of four congruent pairings for each of the digits from 1-9 (i.e., 1-1, 2-2, 3-3 and so on).

The final manipulation concerned the representation of digits as numerals or digit words. For the congruent and incongruent conditions in each language, half of the second items within each pair were presented as Arabic numerals and half were presented as digit words. Each stimulus, thus, occurred twice as a numeral and twice as a digit word.

A computer was used to present the Greek and English digit pairs in random order. The first item from each digit pair was presented auditorily and the second item visually. Greek and English digits (1-9) were recorded digitally by a female Greek-English bilingual, edited using SoundEdit Pro (Macromind), and presented via loudspeakers. The visual stimuli were always presented in the same location on the screen. The presentation sequence was as follows. First, a rhombus prompted the subject to press the space bar on a computer keyboard. A fixation point appeared (1 second) followed by a blank screen (1 second) after which the first item was presented auditorily. The second item in the digit pair was presented visually 250 msec after the onset of the auditory presentation of the first item in the digit pair.

Subjects were instructed to decide whether the digit pairs were congruent or incongruent and to respond by pressing the appropriate key labelled same or different on a computer keyboard. Before testing the subjects were given a practice consisting of 18 similar pairs of stimuli (9 pairs for each language). The presentation of the digit pairs was randomised by computer for each subject. The period between the onset of the second item and the response was taken as a measure of item identification.

Articulation Time

For the measurement of articulation time, a set of 3 digit triads was constructed at random and without replacement using the digits 1-9. This set was varied systematically to make a total of 9 sets of 3 digit triads. The Experimenter presented the digit triad verbally and the subjects were required to memorise the sequence and to articulate it as fast as possible when instructed to do so. The Experimenter counted ten repetitions and measured the time taken by stopwatch. Three articulation measures were taken in each language and a Latin square determined counterbalancing.

Reading Time

For the measurement of reading time, the digits from 1- 9 were randomly varied to construct four lists of 100 items. Two of the printed lists consisted of Arabic numerals and the remaining two lists contained digit words in Greek or English. Consecutive repetition of numbers, as well as ascending or descending sequences of more than two items were avoided. These lists were printed in 10 rows each containing 10 items.

The subjects read the lists as quickly as possible pronouncing each digit individually and audibly and the time taken measured by stopwatch. Prior to the test block the subjects practised reading a list of 50 digits. Language of practice and list order were counterbalanced by a Latin square.

Memory Span

For the measurement of memory span in Greek and English 12 sets of random digit sequences (1- 9) were constructed. Identical items appearing contiguously and ascending and descending sequences were avoided. After two sequences of the initial length, the number of items increased by one and so on.

The sequences were presented visually at the rate of one item per second and each successive item appeared in the same position on the monitor. Six sets comprised Arabic numerals and the remaining sets consisted of either Greek or English digit words. In the control condition the sequences commenced with a length of three items, whereas in the remaining recall conditions for these stimuli the sequences commenced with a length of one item to prevent possible floor effects.

The presentation sequence was as follows. First, the legend READY or ETOIMOI (the Greek equivalent) appeared and prompted the subjects to press the space bar after which a blank screen appeared for 500 msec, followed by a fixation point (500 msec) and the item sequence. When the item sequence terminated a blank screen appeared for 2 sec followed by the legend RECALL or EPANALABATAI which prompted the subjects to commence recall.

For the measurement of memory span under articulatory suppression and random generation conditions, the legend LA-LA or GRAMMATA (the Greek word meaning letters) respectively appeared on the screen 1 second after the sequence was initiated and remained visible for 2 seconds. This prompted the subjects to commence articulatory suppression or the random generation of letters respectively. The remaining presentation sequence was as follows, a blank screen (1 second), a fixation point (1 second), a blank screen (500 msec), and the item sequence. Two seconds after the sequence terminated the legend prompting recall appeared

Thus, for all three recall conditions the recall of sequences was prompted 2 seconds after presentation of the last item. For the articulatory suppression and random generation conditions commencement of the secondary task was signalled 4.5 seconds prior to the presentation of the item sequence and ensured that the secondary tasks commenced before the item sequences were presented.

First, the subjects were first shown two examples of a presentation sequence. Then the articulatory suppression task was introduced and the subjects practised repeating the phrase "la-la" continuously at the rate of one phrase per second in time to a metronome. Two practice memory span trials involving articulatory suppression counterbalanced for language were then presented.

Next, the subjects were introduced to the random generation task and asked to imagine a hat containing the letters of the Greek alphabet from which letters were selected at random, articulated, and replaced. The subjects were reminded that it would be improbable that words, acronyms (e.g., NATO or USA), and regular sequences (e.g., A, B, C, & X, Y, Z) would occur. The subjects then completed two practice trials involving the random production of approximately 20 letters at the rate of one item per second paced by a metronome.

The subjects were instructed to rehearse the material in the specified language and to begin recall without delay on presentation of the recall prompt and were requested to avoid pausing once recall commenced. Memory span was operationalised as the length of the of the last correctly recalled sequence and all recall attempts were recorded both manually and on audio-cassette. If both attempts at the last sequence length were correct a score of 0.5 was added. The order of presentation of trials and the language of instruction and practice were counterbalanced by a Latin square. The subjects were tested individually by a fluent Greek-English bilingual.

8.2.2: Results

Identification Time

The auditory stimuli varied between the languages with consistently shorter time durations for English digits than the Greek equivalents. This difference made it injudicious to compare Greek and English performance directly as subjects were likely to wait until the presentation of the auditory stimulus was complete before responding (Hitch et al., 1989). The item identification data were, therefore, analysed separately by language and is summarised in Figures 8.1 &8.2). The negligible amount of incorrect responses (less than 0.5 per cent) were excluded from the analysis.

The data from the item identification task, were averaged and submitted to a two-way analysis of variance in which representation (numerals or digit words) and congruency (congruent or incongruent were within-subjects factors. For Greek this indicated reliable main effects of item (F (1,23) = 33.96, $p < .0001$) with faster response latencies for numerals (609 msec) than digit words (664 msec) and congruency (F (1,23) = 68.38, $p < .0001$) with faster response latencies for congruent (597 msec) than incongruent (677 msec) items. The interaction between the factors was not reliable (F (1,23) < 1).

A corresponding analysis for the English data revealed reliable main effects of item (F (1,23) = 34.29, $p < .0001$) with faster response latencies for numerals (610 msec) than digit words 664 msec) and congruency (F (1,23) = 12.99, $p < .01$) with faster responses for congruent (616 msec) than incongruent (659 msec) items. The interaction between the factors was also reliable (F (1,23) = 4.70, $p < .05$).

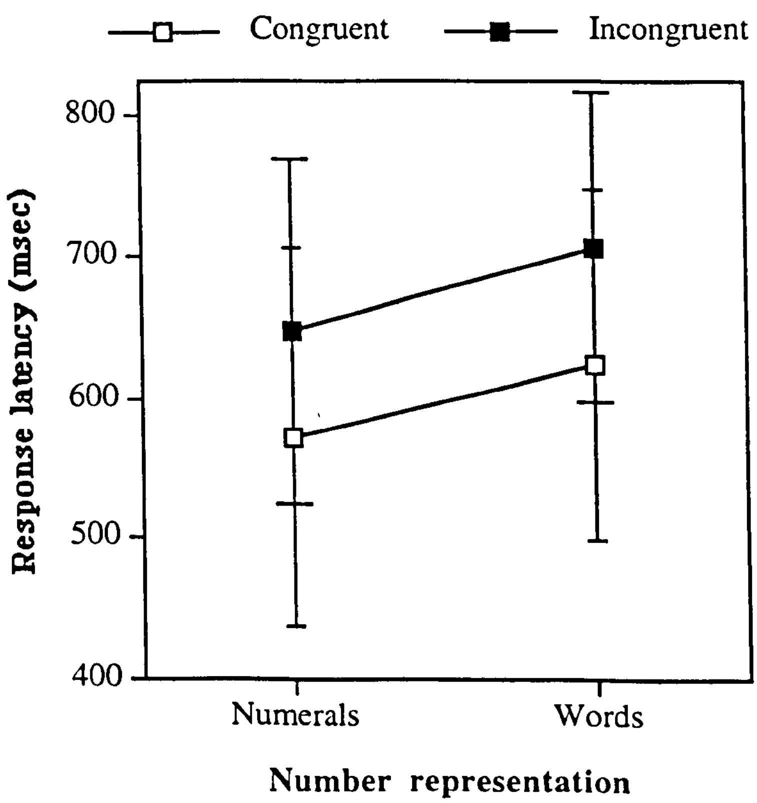

Figure 8.1: Mean response latency (msec) for the cross-modal matching task in Greek.

Analysis of the interaction between item and congruency by simple main effects revealed that response latencies were shorter for numerals than digit words for both congruent (F (1,23) = 26.77, $p < .001$, means = 582 and 650 msec respectively) and incongruent (F (1,23) = 9.65, $p < .01$, means = 638 and 679 msec respectively) items. The difference between congruent and incongruent numerals was reliable (F (1,23) = 11.27, $p < .01$) and marginal for digit words (F (1,23) = 3.02, $p < .10$). The magnitude of the difference between the congruency levels for numerals (56 msec) and digit words (29 msec) varied and this may have resulted in the statistical suggestion of an interaction between the factors. A planned contrast indicated that the difference between the levels of the congruency factor for digit words was reliable ($t = 1.74$, $p < .05$).

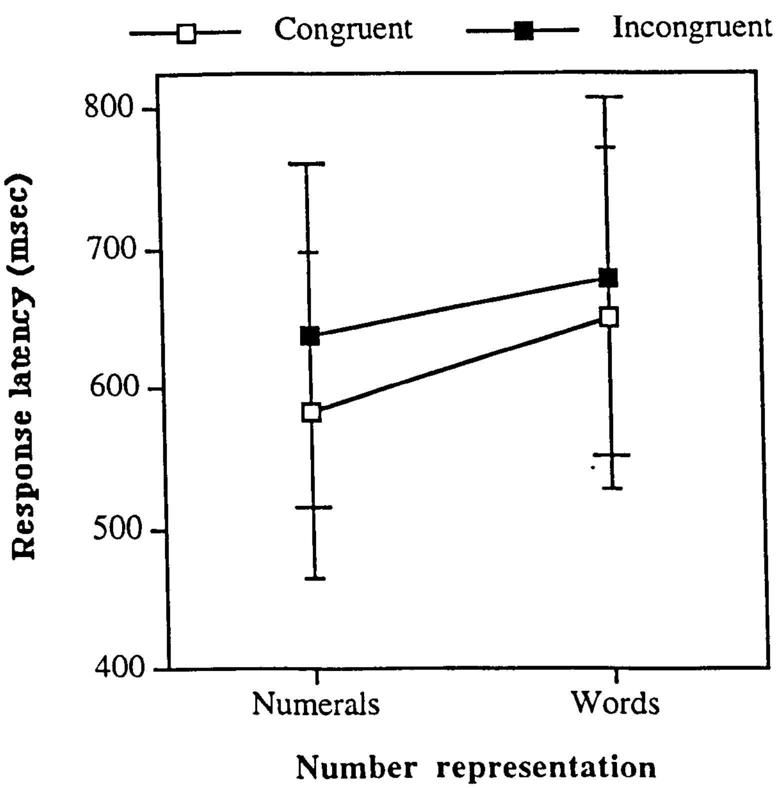

Figure 8.2: Mean response latency (msec) for the cross-modal matching task in English.

To summarise, the results of the cross-modal matching task indicated that the pattern of performance between the languages was identical in that the response latencies were consistently shorter for numerals than for digit words and congruent pairs were identified faster than incongruent pairs. These findings, therefore, supported the view that the faster item identification time for numerals compared to digit words was, plausibly, an influential moderator of the numeral advantage effect.

Articulation Time

The data from the articulation task were averaged and converted into measures of time per digit (msec). Analysis by t-test ($t = 2.24$, $p < .05$) indicated that articulation time was faster in Greek (230 msec/item) than in English (250 msec/item).

Reading Time

The data from the reading task were converted into measures of time per item (msec) and subjected to a two-way analysis of variance in which language (Greek or English) and representation (numerals or digit words) were within-subjects factors and is summarised in Figure 8.3. This indicated a reliable main effect of language (F (1,23) = 8.11, $p < .01$) with a faster reading time in Greek (336 msec/item) than English (355 msec/item) and a reliable interaction between the factors (F (1,23) = 11.20 $p < .01$).

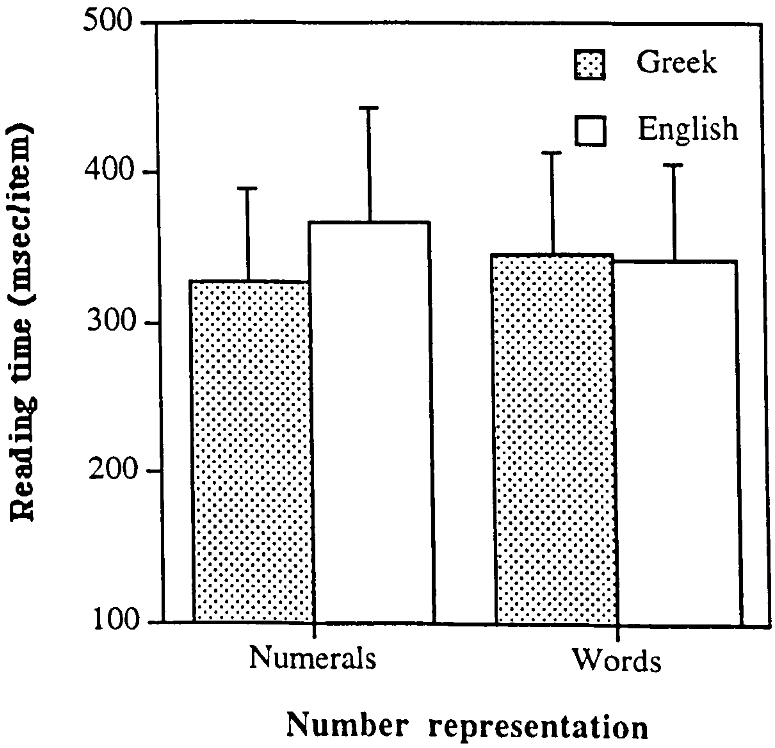

Figure 8.3: Mean reading time (msec/item) for numerals and digit words in Greek and English.

Analysis of the interaction by simple main effects indicated that numerals were read faster in Greek than English (F (1,23) = 19.02, $p < .001$, means = 327 and 367 msec/item respectively) but no language difference was present for digit words (F (1,23) < 1, means = 346 and 343 msec/item respectively). Reading time for numerals was slower than for digit words in English (F (1,23) = 5.52, $p < .05$, mean = 367 and 343 msec/item respectively) but no difference between the number representations was present for Greek ($\underline{F}$ (1,23) = 3.35, means = 327 and 346 respectively).

To summarise, the results of the reading task were consistent with those of Experiments 5 - 7 in that the manipulation of number representation proved to be of no consequence when performance was specified the dominant language (Greek), whereas when the specified language was English reading time for numerals was slower than for digit words. The speech time measures independent of recognition processes indicated that articulation time was faster in Greek than English. The reading time measures indicated that numerals were read faster in Greek than English, whereas digit words were read at equivalent speed between the languages.

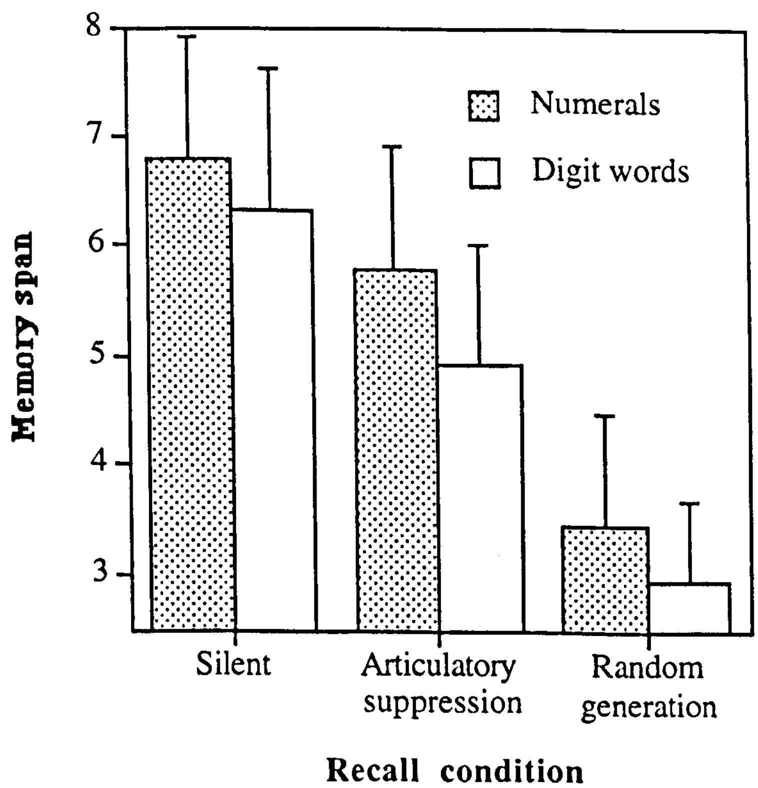

Figure 8.4: Mean memory span for numeral and digit word stimuli under three recall conditions in Greek.

Memory Span

The data from the memory span task was subjected to a three-way analysis of variance in which language (Greek or English), representation (numerals or digit words), and recall condition (silent, suppressed, or random generation) were within-subjects factors and are summarised by language in Figures 8.4 and 8.5. The results indicated reliable main effects of language (F (1,23) = 6.181, $p < .05$) with a larger memory span in Greek (5.05) than English (4.82), representation (F (1,23) = 29.51, $p < .0001$) with a larger span for numerals (5.14) than digit words (4.73), and recall condition (F (2,46) = 164.34, $p < .0001$). Further analysis by t-test indicated that the means for each recall condition (silent = 6.3, suppressed = 5.38, random generation = 3.12) differed amongst themselves (all $p < .001$). The first-order interaction between language and representation was reliable (F (1,23) = 6.70, $p < .05$) but the higher order interaction was not (F (2,46) < 1).

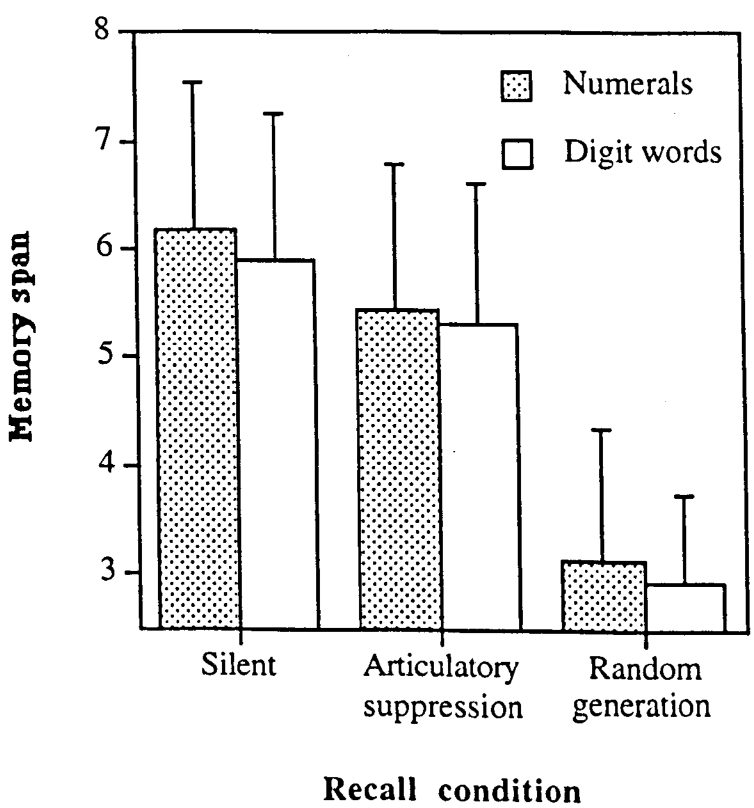

Figure 8.5: Mean memory span for numeral and digit word stimuli under three recall conditions in English.

Analysis of the interaction between the language and representation factors by planned t-tests indicated a larger span for numerals than digit words in Greek (t = 5.78, $p < .001$, means = 5.35 and 4.74 respectively) and English (t = 1.90, $p < .05$, means = 4.92 and 4.72 respectively). The magnitude of the difference was larger for Greek than for

English (0.61 and 0.22 respectively). A between-language difference between Greek and English was present for numerals ($t = 3.31$, $p < .01$) means = 5.35 and 4.92 respectively) but not for digit words ($t = 0.21$, means = 4.74 and 4.72 respectively), and hence the interaction term.

To summarise, the results of the memory span task indicated that memory span for numerals was consistently larger than for digit words in both languages. The present findings, thus, replicated those of Experiments 7 and 8 that showed a numeral advantage effect in both languages of bilinguals: a pattern of results that was unrelated to performance on the speech rate task.

More important, the finding that no interaction effects were associated with the recall condition factor indicated that the numeral advantage effect persisted when subvocal rehearsal was prevented by articulatory suppression and when central executive functioning was disabled. This finding demonstrated that the variation in memory span between numerals and digit words was not moderated exclusively by factors related to chunking. For, if chunking occasions a faster rate of subvocal rehearsal (Zhang & Simon, 1985), articulatory suppression should have eliminated the variation in memory span between the stimuli. Moreover, if, as proposed by Baddeley and Hitch (1974), the central executive component is responsible for reorganising material into chunks, a random generation task would have abolished the numeral advantage effect.

The between-language comparisons showed that memory span for numerals was consistently greater in Greek than English, whereas for digit words performance was equivalent between the languages. These findings, thus, showed that the reading time predicted the between-language relationship but not the within-language relationship in the memory span task.

Correlational Analysis

A series of Pearson correlations was performed on the data to examine the relationship between the estimates of speech rate, item identification, and digit span in Greek and English across the recall conditions and are summarised in Table 8.1.

The results showed that articulation time correlated with memory span for both Greek and English only when recall was under the silent condition. Reading time was correlated with memory span under both silent and suppressed recall conditions for both Greek and English, but not in the random generation condition. For Greek, item identification correlated with memory span under both the suppressed and random generation recall conditions, whereas for English none of the predictor variables were correlated with memory span.

Table 8.1: Correlations between articulation time, reading time, and item identification and memory span in Greek and English under three recall conditions.

	Greek			English		
	Silent	Suppress	Random	Silent	Suppress	Random
Articulation	-.34*	-.21	-.25	-.37*	-.26	.03
Reading	-.69***	-.56***	-.23	-.43**	-.34**	-.11
Identification	-.20	-.29*	-.31*	-.14	-.04	.20

*$p < .05$, **$p < .01$, ***$p < .001$

df for articulation time = 22, df for reading time and item identification = 46

A test of the significance of the difference between correlations (Cohen & Cohen, 1983) indicated a higher degree of association between suppressed memory span and reading time than suppressed memory span and item identification ($t = 2.23$, $p < .05$, $r = -.56$ and $r = -.29$ respectively) when performance was specified in Greek.

The relationship between the speech time estimates and memory span was, thus, consistent with the findings of Hitch et al. (1989) which showed that articulation and reading time were correlated with control memory span, whereas only reading time was correlated with suppressed memory span: this pattern was present for both the dominant and less dominant languages. In addition, the finding that item identification latency and reading time were differently correlated with suppressed memory span was replicated.

To summarise, the results of the correlational analysis indicated variation in the degree to which the speech time and item identification tasks were correlated with memory span performance across the three recall conditions. The most important finding in this respect was that when performance was specified in Greek, response latency for the cross-modal matching task was correlated with memory span when under a secondary task loading that disrupts central executive functioning. This finding suggested that the numeral advantage effect was not mediated exclusively by variation in chunking efficiency between numerals and digit words. Instead, the present findings indicated that the effect is partly moderated by variation in the speed of perceptual processes which occasion a bias in favour of a faster recognition for numerals relative to digit words.

8.2.3: Discussion

The motivation for the present study was to examine the factors that moderate the differential memory span for numeral and digit word representations of number in bilinguals. It was found in Experiment 7 that the numeral advantage effect persisted under conditions in which subvocal rehearsal was prevented and this suggested that the effect arose from differences in the strength of associative connections between the stimuli and a consequent bias in the predisposition toward chunking for numerals. The findings of Experiment 8 were generally consistent with those of Experiment 7 in that articulatory suppression had no effect upon the numeral advantage effect: although in this case, this was restricted to conditions when performance was specified in the less-dominant language. The present study (a replication of Experiment 8 insofar as the memory span tasks were concerned), extended Experiment 7 using Greek-English bilinguals by including a measure of memory span under random generation: a secondary task that disrupts the central executive. It was reasoned that if the superior memory span for numerals over digit words was exclusively mediated by processes related to chunking, the disruption of the component of working memory responsible for transforming information into these more efficient codes would eliminate the numeral advantage effect.

The results of the reading task showed that when performance was specified in the dominant language (Greek), number representation was of no consequence and reading time between the items was equivalent, whereas digit words were read faster than numerals when performance was specified in the less dominant language. The results of the memory span task indicated a larger memory span for numerals than digit words in both Greek and English, thus, performance on the reading task did not predict performance on the memory span task. Crucially, the finding that recall condition did not interact with the remaining factors indicated that the numeral advantage effect persisted when subvocal rehearsal and central executive functioning were disabled and suggested that the effect was independent of processes related to chunking.

The view that the memory span advantage for numerals was not solely mediated by chunking processes was supported by the finding that the measures of item identification (where the speed of perceptual processing was independent of articulation) predicted performance on the memory span task. Moreover, the results of the correlational analysis showed that under a random generation secondary task loading, item identification was the only variable that was associated with memory span for Greek.

Numerals were read at a slower rate than digit words in the less dominant language, whereas numerals were identified faster than digit words when performance did not require the activation of articulatory processes. The pattern of performance in the reading task was mediated by post-recognition processes such as lexical search, phonological recoding, and compilation of the articulatory output codes, whereas item identification performance did not involve speech and was, clearly, unaffected by these variables. Thus, when responses did not require articulatory processing, the pattern of performance between Greek and English was similar with shorter latencies for numerals than digit words. If the assumption that the design of the cross-modal matching task was effective in ensuring that processing was conducted in the specified language was correct, this finding provided some indication that the bilingual digit span effect may be partly mediated by variation in the planning of articulatory gestures between the languages rather than recognition processes and articulation time, per se. This interpretation, however, needed to be constrained as a direct comparison between the languages in the item identification task would have been injudicious given the temporal differences in the duration of the auditory stimuli.

Although the pattern of correlations between memory span and the estimates of speech rate were identical, the relationship between item identification and memory performance varied between the languages. Here, item identification did not correlate with the memory measures for English, whereas for Greek, correlations were present between item identification and memory span performance under articulatory suppression and, critically, under random generation. One obvious explanation for the lack of comparability could be that the cross-modal and memory span tasks differed in respect of language specificity. To explain, for the item identification task the target language was made explicit through the auditory presentation of the initial item in the digit pair. For the memory span task, however, articulatory suppression and verbal random generation tasks prevent phonological loop functioning. Under these circumstances performance was mediated by factors other than subvocal rehearsal and the processing of language-neutral stimuli such as numerals is unlikely to be language specific, and hence the lack of comparability between the languages.

Although variation in the strength of associative connections between the stimuli was proposed as an influential variable in determining the numeral advantage effect (Chapters 6 & 7), this explanation did not account for the present finding or those of Experiment 8 wherein the effect persisted under a random generation secondary task load. For, if the organisation of material into chunks is mediated by the central executive (Baddeley & Hitch, 1974) why did the advantage for numerals over digit words remain when this component of working memory was disabled?

One explanation could be that the involvement of the central executive in recoding information into chunks as envisaged by Baddeley and Hitch (1974) may be limited to conditions under which chunking strategies are explicitly engaged and conscious effort to unitise the material made. In the present study, the stimuli were presented at a constant rate, thus, external cues that may have explicitly encouraged the recoding of material into chunks were absent. It could reasonably be argued that under such conditions, the use of chunking strategies may have been limited and likely to vary across individual subjects. This possibility may have been crucial in making performance on the memory task dependent upon the underlying and implicit variation in strength of associative connections between numerals and digit words rather than an explicit strategy involving chunking.

This notion that could be examined further by varying the degree to which the chunking processes are explicitly encouraged by manipulating the temporal or spatial grouping of the stimuli. Under these conditions when chunking processes are under the explicit control of the central executive we would expect a random generation task to eliminate, or at least reduce, the numeral advantage effect, but this is, clearly, an empirical question.

For the reasons outlined above it could not be concluded that chunking processes are unimportant in moderating the numeral advantage effect. This view was based on the findings of Experiment 8 which were in keeping with the chunking hypothesis and showed that fewer transposition and substitution errors were made for numerals relative to digit words and that random generation induced more of these errors types relative to the remaining recall conditions. To conclude, although the chunking explanation of the numeral advantage effect does not account for the full range of findings of Experiment 9 it seemed plausible that factors related to item identification and chunking interact to produce the memory span advantage for numerals over digit words.

Chapter 9

Output Delay and Bilingual Memory Span

In Experiments 7, 8, and 9, the memory span relationship between dominant and less-dominant language remained intact under concurrent articulation regardless of whether numerals or digit words were presented. This pattern of results suggested that the bilingual memory span effect was not mediated by subvocal rehearsal and phonological loop functioning. This notion was further supported by the findings of Experiments 3 and 4 which demonstrated the influence of long-term memory representations in moderating the bilingual memory span effect, and, to a lesser extent by the findings of Experiment 2 in which articulation time did not predict bilingual auditory digit span. Only the findings of Experiment 1 and of the playing card condition in Experiment 8 indicated that articulatory suppression abolished the memory span advantage in favour of performance in the dominant language present under control recall conditions. A fuller discussion of the factors that may have occasioned the variation in the effects of articulatory suppression between these studies is postponed until Chapter 10. For the purposes of the present Chapter, however, the view that articulatory suppresion did not eliminate differences in bilingual memory span performance was taken. Given that the studies presented thus far generally supported this notion it did not seem unreasonable to adopt such a position.

The ineffectiveness of articulatory suppression in eliminating a superior memory performance in the dominant language, then, could be interpreted in two ways. Firstly, it may be argued that the persistance of superior recall in the dominant language under articulatory suppression is consistent with the view that bilingual memory span effects are mediated principally by factors related to the strength of long-term representations and, thus, the level of relative proficiency between the languages (e.g., da Costa Pinto, 1991; Brown and Hulme, 1992). Secondly, a more contentious interpretation is that the persistence of memory span differentials under articulatory suppression indicated a role of output processes during recall on memory span. Cowan, Day, Saults, Keller, Johnson, and Flores (1992) and Cowan, Wood, Nugent, and Treisman (in press), for example, have questioned the conventional working memory explanation of the word length effect and proposed that this is largely determined by differences in overt speech time during output rather than the rate of covert rehearsal. The experiments presented in this Chapter, then, examined whether variation in output delay between the dominant and less dominant languages could similarly account for the bilingual word length effect.

9.1: Output Delay and Memory Span

Although the effect of word length on short-term memory capacity is a robust finding there is some discussion as to whether actual spoken duration (Baddeley et al. (1975) or phonological structure (Caplan, Rochon, & Waters, 1992) are the critical variables that mediate the capacity of the phonological loop (see, e.g., Baddeley & Andrade 1994; Caplan & Waters, 1994).

Evidence from cognitive neuropsychological studies of adult dysarthics (Baddeley & Wilson, 1985; Vallar & Cappa, 1987) and congenitally dysarthic children (Bishop & Robson, 1989) have demonstrated that word length effects are present in patients that are incapable of engaging in subvocal rehearsal. On the other hand, Waters, Rochon, and Caplan (1992) found no effect of word length in patients with speech apraxia. Taken together these findings suggested that word length effects occur at the level of planning articulatory gestures rather than during subvocal rehearsal.

In one attempt to specify the locus of the word length effect, Cowan, et al. (1992) manipulated the articulatory duration of items in the first and second halves of the presentation sequence in a fixed-length, serial order recall task. The logic of this experiment lay in the notion that words at the beginning of a presentation list are the first to be articulated during recall, therefore, a short word length for the initial items in the sequence results in shorter time delay before the remaining items are attempted. Consequently, recall for subsequent items should be better relative to a condition in which the initial items of the presentation sequence are of longer duration as in the former case there is an increased likelihood of retrieval from the phonological store occurring before the deleterious consequences of trace decay make the signals irretrievable.

Cowan et al. (1992) found that when the initial items in the sequence comprised short words the proportion of correct responses was higher relative to a condition where the articulatory duration of the initial items was longer. The possibility that these findings could be equally attributed to delays in output or a strengthening of long-term representations for the initial items due to a greater number of rehearsal episodes in working memory was examined in a further experiment in which the direction of recall was varied and unknown to the subjects until the end of the presentation sequence.

This manipulation, thus, elegantly contrasted the alternative explanations of the effect as each account (output delays or rehearsal episodes) predicted opposing outcomes. If the effect of initial word length was a function of the number of rehearsal episodes, direction of recall would be of no consequence as this variable would have no impact on the time in which the initial items were stored in working memory. On the other hand, if word length effects were a consequence of output delay the articulation time of the initial items during output would determine performance for both recall directions.

Cowan et al. (1992) found that word length in the first half of the sequence was a highly influential factor in determining the proportion of correct responses for forward recall, whereas for backward recall word length effects were observed in the second half of the list (i.e., for items presented last and recalled first). Cowan et al. (1992), thus, provided convincing evidence in support of the output time hypothesis and concluded that the word length effect "must be accounted for largely by the effect of output delay, rather than primarily by covert articulatory processes" (p.14).

Avons, Wright, and Pammer (1994) found that the magnitude of the word length effect was greater for serial recall than probed recall tasks: a pattern that persisted when subvocal rehearsal was encouraged by increasing the retention interval after presentation by 5 seconds. These findings were consistent with the view that word length effects could not be explained solely in terms of variation in the rate of subvocal rehearsal as this account would have predicted an equivalent effect of word length between the recall tasks. Avons et al. (1994), however, proposed that word length effects could be accommodated by working memory theory if the capacity of the phonological loop was not viewed as being exclusively limited by temporal constraints.

Evidence for a modified view of the variables that mediate the capacity limits of the phonological loop has been provided by Hulme, Maughan, and Brown (1991), Roodenrys, Hulme, & Brown (1993), and Henry and Millar (1991). In these studies the influence of factors independent of speech rate (and thus output time) have been shown to be influential determinants of memory capacity. A further area that has received recent attention is the role of long-term memory representations in mediating short-term memory. Hulme, Roodenrys, Brown, and Mercer (1995) and Brown and Hulme (1995), for example, have proposed that long-term phonological representations assist the retrieval of decayed traces held in short-term storage through the process of redintegration (see, e.g., Nairne, 1990; Schweickert, 1993).

The studies presented in this Chapter applied the Cowan et al. (1992) paradigm to an examination of the effect of output delay in mediating the variation in bilingual memory capacity (e.g., Ellis & Hennelly, 1980; da Costa Pinto, 1991; Elliot, 1992; Chincotta & Hoosain, 1995). Ellis and Hennelly (1980) attributed a larger auditory digit span in English than Welsh by Welsh-English bilinguals to differences in articulation duration for digits between the languages (as established by an Arabic numeral reading task) -- the so-called bilingual word length effect. The notion that a superior digit span in English was mediated by variation in articulatory duration for digit names between Welsh and English was strengthened by a finding that for digit word stimuli the language difference was abolished under articulatory suppression.

As as been argued in this thesis, however, the Ellis and Hennelly (1980) account of the bilingual word length effect has proved to be over simplistic. Da Costa Pinto (1991) and Brown and Hulme (1992), for example, as well as the findings of Experiments 7 - 9, have demonstrated the persistence of bilingual digit span effects under articulatory suppression: Moreover, the findings of Experiments 5 - 8 have shown that the representation of digits as either Arabic numerals (1, 2, 3, etc.) or digit words (one, two, three, etc.) is a variable of some consequence when examining the effect of articulatory suppression on bilingual digit span varies. Additionally, in Chapters 3 and 5 it was argued that methodological problems associated with the Ellis and Hennelly (1980) study make the conclusion that articulatory suppression abolished the effect of word length between Welsh and English digit span difficult to sustain.

It seems clear, then, that accounts of bilingual memory performance based on speech rate and the rate of subvocal rehearsal alone do not capture the full range of findings. The question as to the role of output delay in mediating the bilingual word length effect, however, has been left open. Experiment 10 examined the relative effect of output delay on immediate memory capacity between the languages of Spanish-dominant, Spanish-English bilinguals. This was achieved by manipulating the word length of items in the initial and subsequent serial positions of the presentation sequence and varying the direction of recall. This design allowed a test of the extent, if any, to which the bilingual memory span effect is mediated by variation in output delay between the languages and examined whether the persistance of bilingual memory span effects under articulatory suppression may be attributed to output processes rather than the rate of subvocal rehearsal.

It was reasoned that the slower speech rate normally associated with performance in the less-dominant language would occasion longer output delays relative to the dominant language, therefore, the differential in articulation time during recall could be an important determinant of the bilingual word length effect. If output delay is one crucial variable determining memory span differences between the languages the word length of items in the initial positions of the output sequence would be influential in mediating recall performance for both forward and backward recall. Given a hypothesised slower speech rate in the less-dominant language, however, the magnitude of the effect of output delay would be greater in English than Spanish.

Such a finding, of course, would not exclude the possibility that the effect of output delay is related to variation in the strength of long-term representations between the languages. Under these circumstances, the redintegrative process (e.g., Hulme et al., 1995) is likely to be more efficient in assisting the pattern completion of decaying traces in the phonological store in the dominant language than the less dominant one. One feature of the Cowan et al. (1992) methodology is that it allowed the rate of decay from the phonological store to be traced. This was achieved by plotting the proportion of correct responses for each serial position as a function of the estimated elapsed articulation time prior to recall of the item in question.

If the variation in memory span between the languages is mediated exclusively by differences in output delay between Spanish and English, the rate of decay from the phonological store as a function of elapsed articulation prior to recall for each language would be described by a single linear function. An alternative hypothesis is that the long-term memory representations for the items would be stronger in the dominant than in the less dominant language. This account leads to the prediction that the variation in strength of long-term representations between the languages would be indicated by a higher intercept for Spanish than for English. Such a finding would support the notion that the effect of output delay is intrinsically linked to redintegrative processes that are dependent upon the availability of representations in long-term memory.

9.2: EXPERIMENT 10

9.2.1: Method

Subjects

The subjects were 16 Spanish-dominant, Spanish-English bilinguals registered with a British University under the auspices of the ERASMUS academic exchange program. The subjects had studied English for an average of 9 years and were paid for participation in the experiment.

Materials

For the measurement of memory span, word pools of 6 short (2 syllable) and 6 long (3 syllable) words (mean frequency = 255 per million) in Spanish and English were selected using frequency counts for each language (Juilland & Chang-Rodriguez, 1964; Kucera & Francis, 1971 respectively, Appendix 2.8). Four trial types were constructed in which the first three and last two items in the sequence consisted of either short words or long words selected at random from the respective word pools without replacement. Four blocks, each containing 12 trials, were constructed for Spanish and English. Each block consisted of two, random 5-item sequences of each trial type together with an additional four filler sequences in which long and short words were alternated. Half of the trial types were randomly selected for the backward recall condition within each block.

For the measurement of articulation time, two word triads were constructed from each pool without replacement. The triads were varied systematically to make a total of eight sets of two triads for each word pool. For the measurement of reading time, 100 items were randomly generated for each pool with the restriction that identical words should not be contiguous and these were printed in 10 rows each consisting of 10 items.

Procedure

The subjects were tested individually by a fluent bilingual and the procedure followed that described in the Cowan et al. Experiment 3 (1992) . Each subject received four blocks of trials for each language. The words were presented at the rate of one item per two seconds and commencement of the presentation sequence was prompted by the subject pressing on a designated key on a computer keyboard once the legend READY or PREPARADO (the Spanish equivalent) appeared on the screen. Two seconds after the sequence terminated one of two recall cues appeared on the screen. A blue arrow pointing rightwards indicated that forward recall was required and an orange arrow pointing leftwards prompted backward recall. The subjects were, thus, unaware of the direction of recall until the presentation sequence terminated. The subjects were requested to guess any items they were unable to remember.

Before testing, the subjects were asked to read the items aloud in both Spanish and English to test reproduction. The subjects were, then given eight practice sequences for which a Latin square determined counterbalancing for recall order and language.

Finally, measures of speech time were taken. Half the subjects performed the articulation task first and then the reading task and for the other half, the order to these two tasks was reversed. For the articulation task the experimenter read a word triad and subjects were required to memorise the sequence and commence articulating as fast as possible until instructed to stop when prompted to do so. The subjects continued articulating the triad until ten repetitions were counted by the Experimenter and the time taken was measured by stop watch. For the reading task, the subjects read the lists as quickly as possible pronouncing each word audibly and the time taken was measured by stop watch.

9.2.2: Results

Speech Time

The data from the articulation and reading tasks were transformed into measures of time per item (msec/word) and are summarised in Table 9.1. The articulation time data were subjected to a two-way analysis of variance in which language (Spanish or English) and word length (short or long) were within-subjects factors. This revealed reliable main effects of language (F (1,15) = 51.53, $p < .0001$) with a shorter articulation time in Spanish than English (means = 312 and 380 msec/word respectively), and word length (F (1,15) = 130, $p < .0001$) with a shorter articulation time for short words than long words (means = 293 and 399 msec/word respectively). The two-way interaction between the factors was reliable (F (1,15) = 14.32 $p < .01$).

Table 9.1: Mean (SD) articulation and reading time (msec/word) for short and long words in Spanish and English.

	Spanish		English	
	Short words	Long words	Short words	Long words
Articulation	274	348	310	449
time	(42)	(56)	(50)	(89)
Reading	351	400	412	484
time	(23)	(27)	(32)	(42)
Mean	313	374	361	467

Analysis of the interaction by simple main effects indicated that short words were articulated faster than long ones for both Spanish (F (1,15) = 31.51, $p < .0001$, means = 274 and 348 msec/word respectively) and English (F (1,15) = 110.49, $p < .0001$, means = 310 and 449 msec/word). Language differences were present for both short (F (1,15) = 7.21, $p < .05$) and long (F (1,15) = 55.73, $p < .0001$) words. Inspection of the means indicated that the magnitude of the language difference was greater for long words (101 msec/word) was greater than for short words (36 msec/word), hence the interaction term.

The reading time data were subjected to a corresponding analysis of variance. This revealed a main effect of language (F (1,15) = 176.18, $p < .0001$) with a faster reading time for Spanish than English (means = 376 and 448 msec/word respectively), and word length (F (1,15) = 176.18, $p < .0001$) with a shorter reading time for short words than long words (means = 382 and 442 msec/item respectively). The interaction between the factors was also reliable (F (1,15) = 8.92. $p < .01$).

Analysis of the interaction by simple main effects indicated that short words were read faster than long ones in both Spanish (F (1,15) = 44.28, $p < .0001$, means = 351 and 400 msec/word respectively) and English (F (1,15) = 93.40, $p < .0001$, means = 412 and 484 msec/word). A language difference was present for both short (F (1,15) = 62.88, $p < .0001$) and long (F (1,15) = 117.55 $p < .0001$) words. In both cases words were read faster in Spanish. The magnitude of the language difference was greater for long words (84 msec/word) than for short words (61 msec/word), hence the interaction term.

To summarise, the outcome of the articulation and reading tasks was identical in that both measures showed a faster speech rate for Spanish than English with short words articulated faster than long ones. In the analyses of the articulation and reading time data, the interaction terms were due to differences in the magnitude of the language difference across the word length factor.

Proportion Correct

Forward Recall

The proportion of correct responses for the forward and backward trials was averaged for each subject and the data for each recall condition analysed separately. The forward recall order data were entered into a four-way analysis of variance in which language (Spanish or English), first-half word length (short or long), second-half word length (short or long) and serial position (1-5) were all within-subject factors. For forward recall the first three serial positions were either short or long, whereas for the backward recall order the word length of first two items in the sequence was varied, however, we refer to short and long halves for ease of presentation.

The analysis revealed a reliable main effect of language (F (1,15) = 16.43 $p <$ .01) with a larger proportion of correct responses for Spanish than English (0.83 and 0.72 respectively), and second half word length (F (1,15) = 8.27, $p <$ .01) with a higher proportion of correct responses associated with the short second-half than the long second-half (0.80 and 0.75 respectively). A main effect of serial position was also present (F (4,60) = 18.52, $p <$ .0001) with a higher proportion of correct responses present for the items at the initial positions. Further analysis by t-test indicated that all the comparisons were reliable (all $p <$ .05) bar those between the final serial position and the third and fourth position.

The three-way interaction between the language, first-half, and second-half word length factors was reliable (F (1,15) = 5.43, $p <$ .05) and is summarised in Figure. 9.1. Further analysis by simple main effects indicated a higher proportion of correct responses for Spanish than English at both the short first-half--long second-half (F (1,15) = 10.05, $p <$ .01, means = 0.85 and 0.69 respectively) and the long first-half--short second-half conditions (F (1,15) = 7.19, $p <$ .05, means = 0.84 and 0.71 respectively). There was no language difference when the sequences comprised either short words ($F <$ 1) or long words (F = 2.32).

For Spanish, the manipulation of first-half word length had no effect on recall performance when the second-half comprised either short ($F <$ 1) or long words (F = 2.95). Similarly for English, no effect of first-half word length was present for the short (F = 3.39) or long ($F <$ 1) second-half word length condition. Inspection of the means (Figure. 9.1) suggested that, for English, there was a marginal effect of first-half word length when the second-half of the sequence consisted of short words (F (1,15) = 2.95, p = 0.09) with a trend toward a greater proportion of correct responses for the short first-half words that long ones (means = 0.80 and 0.69).

The manipulation of second-half word length, however, did have an effect on the proportion of correct responses in the first-half of the sequence although this varied between the languages. For Spanish the effect of second-half word length was present when the first-half of the sequence contained long words. Here, a higher proportion of correct responses was present when the second half of the sequence contained short words compared to long ones (F (1,15) = 5.29, $p < .05$, means = 0.85 and 0.77 respectively). However, when the first half of the sequence comprised short words no effect of second-half word length was observed ($F < 1$).

For English, an effect of second-half word length was present when the first half of the sequence consisted of short words (F (1,15) = 10.15, $p < .01$) with a greater proportion of correct responses for the short second-half words than the long ones (means = 0.80 and 0.69 respectively). Second-half word length had no effect when the first half of the sequence consisted of long words ($F < 1$).

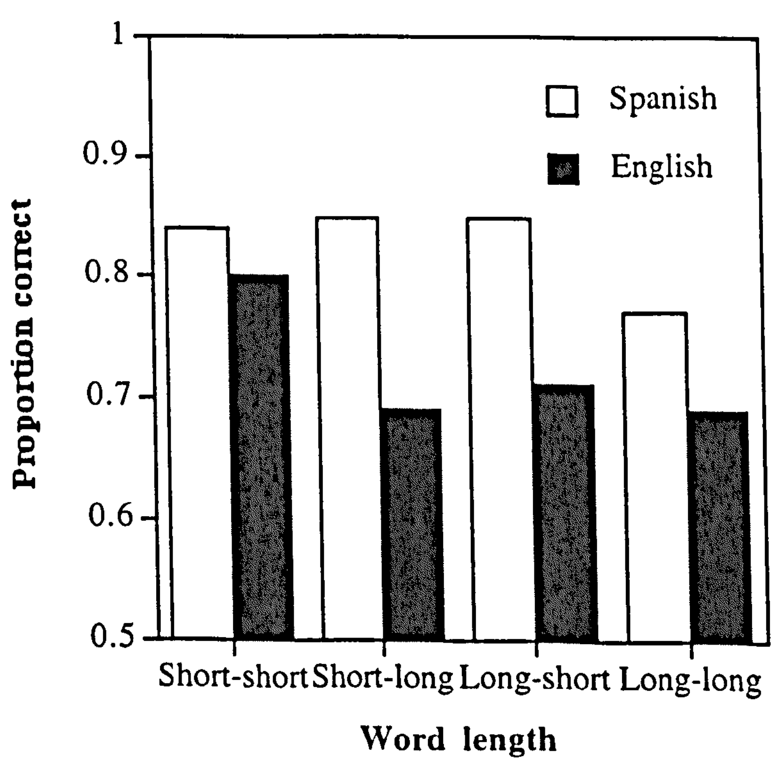

Figure 9.1: Mean proportion correct for first half, and second-half word length factors in Spanish and English for the forward recall condition.

These results indicated that the presence of the three-way interaction was due to the different outcome between the languages as a consequence of the manipulation of the second-half word length factor and not an effect of first-half word length.

Overall, the findings of the forward recall task indicated that the word length of items in the second-half of the sequence was crucial in determining recall perfromance. The effect of the second-half word length manipulation, however, differed between the languages. For Spanish, the effect was present for the long first-half word length condition, whereas for English, the effect was observed when the first-half contained short words. In other words, when performance was specified in English, the proportion of correct responses diminished whenever the sequence contained long words, whereas for Spanish, the proportion of correct response was lower only when all the items were long. Notwithstanding the variation between the languages, one finding was clear, the length of items in the first-half of the sequence had no effect on recall, whereas the length of words in the second half of the list did.

<u>Backward Recall</u>

The backward recall order data were entered into a four-way analysis of variance. This indicated a reliable effect of first-half word length ($\underline{F}$ (1,15) = 7.76, $\underline{p} < .05$) with a higher proportion of correct responses associated with the short first-half presentation condition (and recalled last) than the long first-half one (means = 0.81 and 0.75 respectively). The main effect of serial position was also reliable ($\underline{F}$ (4,60) = 16.56, $\underline{p} < .0001$) with a greater number of correct responses for the last serial positions (i.e., those items recalled first).

The interaction between the first-half and second-half word length order factors was reliable ($\underline{F}$ (1,15) = 6.10, $\underline{p} < .05$) and is summarised in Figure. 9.2. Further analysis by simple main effects revealed that the only difference present was that between the short and long first-half presentation conditions across the long second-half word length factor ($\underline{F}$ (1,15) = 12.27, $\underline{p} < .01$, means = 0.81 and 0.71

respectively). This finding indicated that the effect of first-half word length occurred only when the second-half (those items recalled first) contained long words.

In short, the results for the backward recall condition indicated that the word length of the initially presented items (and recalled last) moderated recall performance. The interaction between the first- and second-half word length factors indicated that the effect of first-half word length was present only when long items were presented in the second half of the sequence. There were no main effects or interactions associated with the language factor.

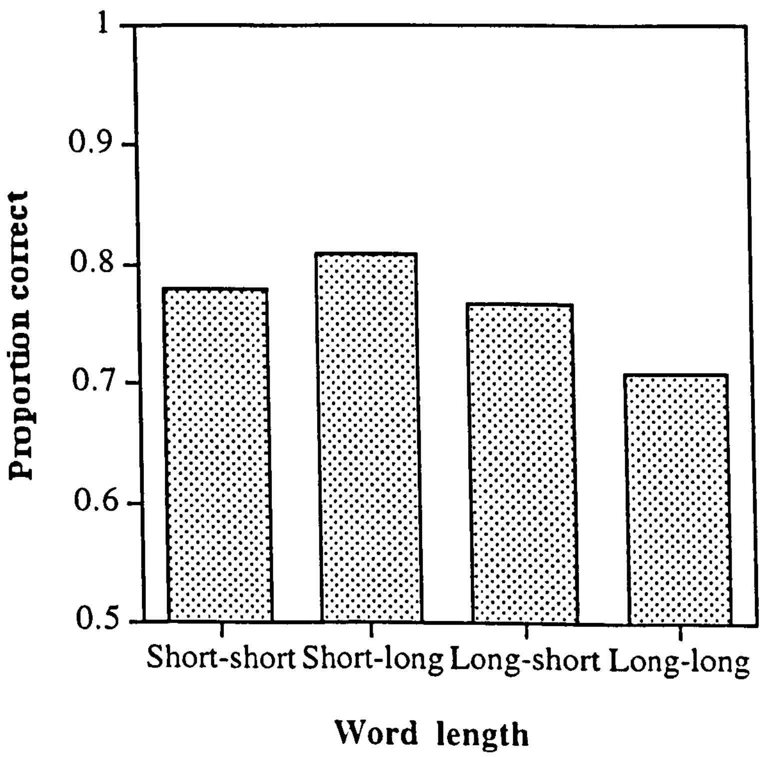

Figure 9.2: Mean proportion correct for first-half and second-half word length factors for the backward recall condition.

To summarise, the results of the forward and backward recall tasks did not support the view that word length effects in immediate recall may be accounted for in terms of output delays. Instead, the present findings indicated that when the articulation duration of items did have an effect on the proportion of correct responses this was consistently present in the second-half of the output sequence (regardless of the direction of recall) and not in the first-half of the recall sequence as reported by

Cowan et al. (1992). For both recall directions a higher proportion of correct responses was present for short word second-half condition of the recall sequence relative to the long second-half condition. Moreover, a language difference was present in the forward recall condition (with a greater proportion of correct responses for Spanish than English), whereas in the backward recall condition the proportion of correct responses was equivalent between the languages. This finding indicated that the articulation duration of items was not an important determinant of language differences when recall was specified in reverse order.

Memory Decay

In order to illustrate the time course of decay from the phonological store the proportion of correct responses was plotted as a function of articulation time elapsed prior to recall of the item in question. According to the strong form of the output delay hypothesis, the word length effect is mediated by variation in the time taken to articulate items during recall. If this is so, the rate of decay from the phonological store should be consistent between the languages and accounted for by a single linear function. In addition, if memory span performance was determined exclusively by output delays, an equivalent proportion of correct responses should be present for the first item recalled regardless of whether the specified language was Spanish or English given that no time would have elapsed before recall of the initial item. Given the likelihood that the phonological representations would be stronger in Spanish than for English, however, the redintegration of decaying traces in short-term store should be more effective in the dominant than the less-dominant language. This should be illustrated by a higher y intercept for Spanish than English (Hulme et al., 1991).

The mean proportion of correct responses for short and long word sequences as a function of pronunciation time elapsed prior to recall were calculated by averaging the articulation and reading time estimates of speech rate for short and long words (Cowan et al., 1992). The last items recalled were excluded from the analysis in order to avoid unnecessary noise arising from the effects of recency.

For the forward recall condition the fit to the Spanish data was described by the linear function $y = -0.228x + 0.97$ ($R^2 = 0.95$, $p < .001$) and the English data by $y = -0.213x + 0.87$ ($R^2 = 0.93$, $p < .01$) and are represented in Figure 9.3. Inspection of the Spanish and English means indicated that the data were not best described by a single linear function. The intercept for the Spanish data was higher than for English (0.97 and 0.87 respectively, $t = 2.34$, $p < .05$).

For the backward recall condition the fit to the Spanish data was described by the linear function $y = -0.233x + 0.90$ ($R^2 = 0.85.$, $p < .01$) and the English data by $y = -0.225x + 0.90$ ($R^2 = 0.75$, $p < .05$) and are illustrated in Figure 9.4. The gradients for the Spanish and English data were comparable and the intercepts for the Spanish and English functions were identical (0.90).

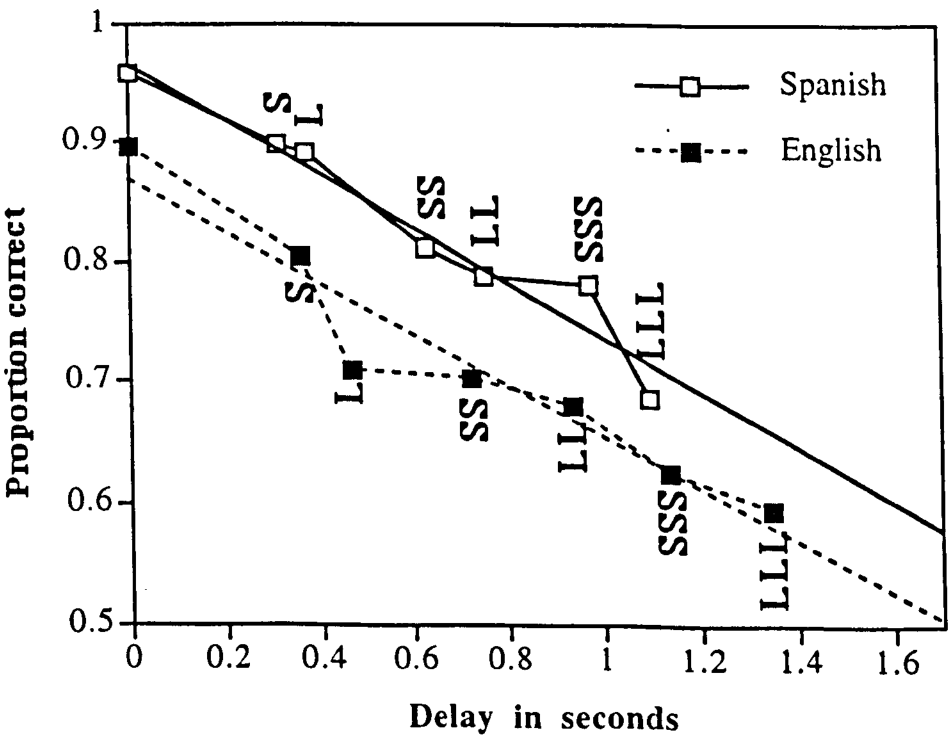

Figure 9.3: Mean proportion correct as a function of the estimated total of elapsed articulation time prior to the recall attempt and linear regressions in Spanish (solid line) and English (broken line) for forward recall. Labels nearest each data point indicate the sequence of short (S) and long (L) words articulated prior to the item in question.

The memory decay functions suggested that the difference between the dominant and less dominant languages in the forward recall condition was likely to be a consequence of differences in the strength of long-term representations. This was illustrated by the different intercepts for Spanish and English (0.97 and 0.87 respectively) and a comparable gradient between the functions (-0.228x and -0.213x respectively). By contrast, in the backward recall condition the intercepts were identical between the languages, and the language difference between the gradients was smaller than for the forward recall data (Spanish = -0.233x, English = -0.225x). The plots of the proportion of correct responses as a function of elapsed time prior to recall, thus, suggested that decay from the phonological store occurred at broadly equivalent rates between the languages and for both recall conditions.

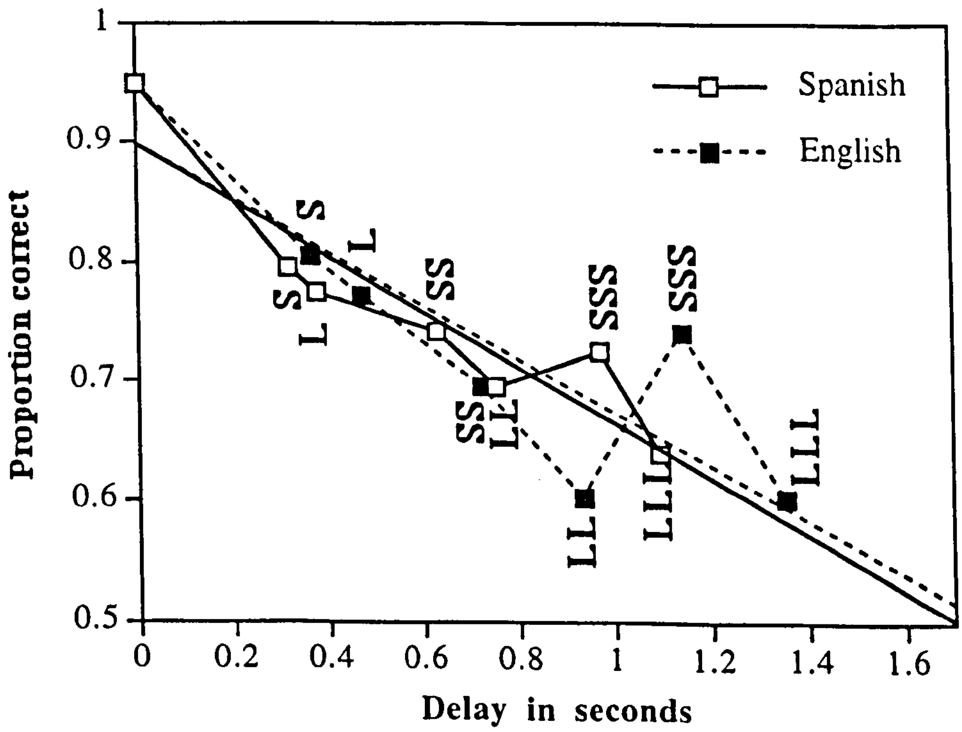

Figure 9.4: Mean proportion correct as a function of the estimated total of elapsed articulation time prior to the recall attempt and linear regressions in Spanish (solid line) and English (broken line) backward recall.

9.2.3: Discussion

The results of Experiment 10 did not support the view that word length effects were mediated by variation in output delay as suggested by Cowan et al. (1992). Instead, the findings indicated that the word length of the second-half of the sequence was critical in determining recall performance: a relationship that was present for both directions of recall. Moreover, although recall performance was superior in Spanish than English for forward recall, no language difference was present for backward recall. This finding indicated that factors associated with speech rate and long-term representation were of no consequence in moderating performance for the backward recall task.

One obvious explanation of the divergence between the present findings and those of Cowan et al. (1992) could lie in a difference in word frequency between the studies. According to Kucera and Francis (1971), the Cowan et al. (1992) word pool consisted of an average frequency of about than one per million. By contrast, the average frequency of the items in Experiment 1 was 255 per million. It was reasoned that when bilingual performance is examined, the use of low-frequency items comparable to those of Cowan et al. (1992) would have been injudicious given the likelihood that the processing of low-frequency words would be fundamentally different between the dominant and less-dominant languages.

So, what could the consequences of using low-frequency items when examining the effects of output delays on immediate recall have been? Hulme and colleagues (1991, 1995) have demonstrated that long-term representations, particularly phonological ones, provide crucial support in memory span tasks through the process of redintegration. This suggests that items with weak long-term representations are likely to decay at a rapid rate from the phonological store as the restorative action of the articulatory control process would be relatively inefficient compared to items with strong long-term representations.

The use of low frequency words by Cowan et al. (1992) may, therefore, have resulted in a disproportionate involvement of the phonological loop relative to high frequency words. Under these circumstances, the word length of the initially presented items would be highly influential in mediating the probability of recovering traces in the phonological store before the signal decayed irretrievably. As reported by Cowan et al. (1992), long articulation times during output increased the likelihood of unsupported items in the phonological store perishing beyond the point of recoverability and the same pattern of results was observed regardless of the direction of recall. This notion was supported by the present finding that when forward recall was specified in the language with weaker long-term representations (English) a trend toward an effect of output delay was observed.

High frequency items, on the other hand, enjoy stronger long-term representations and traces within the phonological store are likely to be renewed and sustained more efficiently relative to low frequency ones. For items with strong long-term representations, the cyclical process of subvocal rehearsal strengthens the associative connections between traces in the phonological store and long-term memory making these items less prone to decay and more readily available for recall than low frequency ones. Under these circumstances, the effects of output delay arising from the initially recalled items are less likely to have a deleterious effect on recall for subsequent items as the connections between long-term memory and short-term memory are capable of maintaining phonological traces for the later items in a state of activation and more readily available for recall. For high frequency items, then, the factors affecting recall are less likely to be related to output delays and more to do with the limitations of subvocal rehearsal to refresh the items in the phonological store: a factor mediated by the temporal capacity of the phonological loop itself.

The findings of Experiment 10 were consistent with the explanation that word length effects are mediated by subvocal rehearsal and phonological loop capacity rather than output delay. This is best illustrated as follows. The mean articulation durations for long words in Spanish and English were 348 msec and 449 msec respectively. Now, the temporal capacity limits of the phonological loop are generally estimated to lie within the range of 1.5 to 2 seconds (Baddeley et al., 1975), thus, it was not unreasonable to assume an average temporal phonological loop capacity of around 1.75 seconds. This suggested that the initial three items in the presentation sequence, regardless of language or word length, would not exceed this limit. Under these circumstances, therefore, the word length of the last two items were crucial in determining whether or not information was subvocally rehearsed and maintained within the phonological store. Articulation time was used to illustrate this point in preference to the reading time estimate of word length as the former is the more direct measure of subvocal rehearsal rate (Hitch, Halliday, & Littler, 1989).

In the case of Spanish, this suggested that the limits of an average phonological loop capacity would be approximated only when all the items in the sequence consisted of long words (1.74 seconds). In the case of English, the estimated phonological loop capacity would be exceeded whenever the sequence contained two long words (898 msec) and three short words (930 msec), but not when all the items were short (1550 msec). This is precisely the pattern of results indicated by the three-way interaction for the forward recall condition where, for Spanish, the proportion of correct responses was poorer only when the sequence consisted of long words, whereas for English a decrement in performance was present whenever the sequence contained long words.

If this account of the differences in processing between low and high frequency items was correct, it suggested that the effect of output delay on immediate recall varies dependent upon on the availability and strength of long-term representational support. The results of Experiment 10 indicated that for high frequency items immediate memory performance was determined by whether the total temporal duration of the presentation sequence exceeded the capacity of the phonological store. For, it was only when the capacity limit became overloaded that the renewing action of the articulatory control process faltered and a consequent disruptive effect on recall performance became manifest.

It was reasoned, therefore, that the effects reported by Cowan et al. (1992) were likely to have been a consequence of the selection of items for which the strength of phonological long-term representations were relatively weak. This explanation was tested in Experiment 11 by substituting high-frequency items with words of an average frequency of approximately 10 per million in Spanish and English. Ideally, it would have been preferrable to use items of comparable frequency to those selected by Cowan et al. (1992). This was not possible, however, as the Spanish word frequency-count at our disposal did not list items with a frequency of less that 10 per million. A frequency of approximately 10 per million, however, increased the likelihood that the items were processed as words rather than nonwords when recall was specified in the less dominant language.

9.3: EXPERIMENT 11

9.3.1: Method

Subjects

The subjects were 16 Spanish-dominant, Spanish-English bilinguals registered with a British University under the auspices of the ERASMUS academic exchange program and had not participated in Experiment 1. The subjects were comparable to those selected for Experiment 9 in terms of age and in the number of years spent studying English (approximately 9 years) and were paid for participation.

Materials & Procedure

For the measurement of memory span word pools of 6 short (2 syllable) and 6 long (3 syllable) words (mean frequency = 11 per million) in Spanish and English were selected using frequency counts for each language (Juilland & Chang-Rodriguez, 1964; Kucera & Francis, 1971 respectively, Appendix 2.9). All other procedural details were identical to those described for Experiment 10.

9.3.2: Results

Speech Time

The data from the articulation and reading tasks were transformed into measures of time per item (msec/word) and are summarised in Table 9.2. The articulation time data were subjected to a two-way analysis of variance in which language (Spanish or English) and word length (short or long) were within-subjects factors. This revealed reliable main effects of language (F (1,15) = 144.40, $p < .0001$) with a faster articulation in Spanish than English (means = 338 and 501 msec/word respectively), and word length (F (1,15) = 77.82, $p < .0001$) with a faster articulation for short words than long words (means = 385 and 456 msec/word respectively). The two-way interaction between the factors was not reliable (F (1,15) = 1.13 $p > .05$).

The reading time data were subjected to an identical analysis of variance. This revealed main effects of language (F (1,15) = 125.48, $p < .0001$) with a faster reading rate for Spanish than English (means = 384 and 491 msec/word respectively), and word length (F (1,15) = 66.54, $p < .0001$) with a faster reading time for short words than long words (means = 407 and 467 respectively). The interaction between the factors was also reliable (F (1,15) = 27.51 $p < .0001$).

Table 9.2: Mean (SD) articulation and reading time (msec/word) for short and long words in Spanish and English.

	Spanish		English	
	Short words	Long words	Short words	Long words
Articulation	306	371	463	541
time	(49)	(52)	(75)	(74)
Reading	366	401	448	534
time	(32)	(32)	(55)	(55)
Mean	336	386	456	534

Analysis of the interaction by simple main effects indicated that short words were read faster than long ones in both Spanish (F (1,15) = 11.14, $p < .01$, means = 366 and 401 msec/word respectively) and English (F (1,15) = 67.22, $p < .0001$, means = 448 and 534 msec/word). A language difference was present for both short (F (1,15) = 36.42, $p < .0001$) and long (F (1,15) = 96.18, $p < .0001$) words. In both cases the items were read faster in Spanish. The magnitude of the language effect was greater for long words (133 msec/word) than for short words (82 msec/word), hence the interaction term.

To summarise, the analyses of the articulation and reading tasks were identical in that both measures showed a faster speech rate for Spanish than English with short words articulated faster than long ones. The interaction term present in the reading task was due to differences in the magnitude of the effects across conditions. These findings indicated that short words took less time to articulate than long words and performance was faster in Spanish than English.

Proportion Correct

Forward Recall

The proportion of correct responses for the forward and backward recall orders were analysed in the manner described for Experiment 10. For the forward direction of recall the analysis of variance revealed a main effect of language (F (1,15) = 26.54, p < .0001) with a larger proportion of correct responses for Spanish than English (0.83 and 0.73 respectively), and serial position (F (4,60) = 30.03, p < .0001) with a higher proportion of correct responses for items in the initial serial positions.

The two-way interactions between language and first-half length (F (1,15) = 7.28, p < .05), language and serial position (F (4,60) = 3.76, p < .01), and first-and second-half word length (F (1,15) = 4.55, p < .05) were reliable. These interactions were qualified by the presence of reliable second-order interactions between language, first-half word length, and serial position (F (4,60) = 3.26, p < .05) and language, second-half word length and serial position (F (4,60) = 2.72, p < .05).

The three-way interaction between language, first-half word length, and serial position was analysed by simple main effects and is summarised in Figure 9.5. This revealed a difference between the short and long first-half word length for Spanish at the fourth serial position (F (1,15) = 5.14, p < .05, means = 0.82 and 0.63 respectively), whereas no differences were present for English. A language difference was present in the short first-half condition for the last three serial positions (all 10.00 < F < 14.00, $p < .01$) with a greater proportion of correct responses for Spanish than English. The language difference for the final serial position in the long first-half condition was marginal ($F(1,15) = 3.92$, $p = .07$). These findings indicated that when the first half (recalled last) of the presentation sequence contained short words a greater proportion of correct responses was present compared to the condition in which the first half contained long words. However, the effect of first-half word length was present when performance was specified in Spanish but not English.

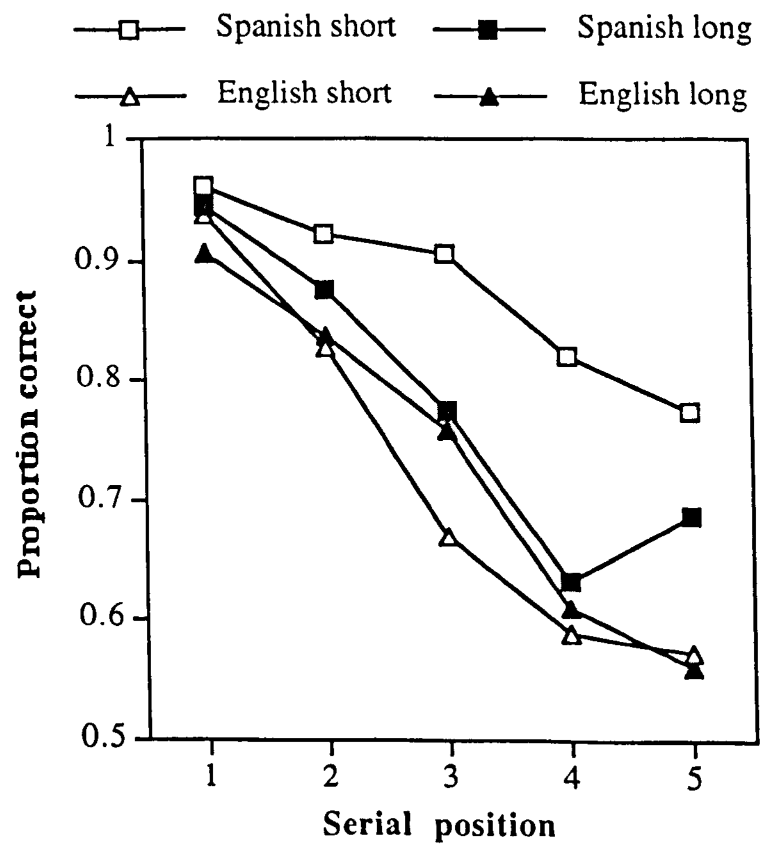

Figure 9.5: Mean proportion correct for the short and long first-half word length condition for Spanish and English as a function of serial position in the forward recall condition.

The interaction between language, second-half word length, and serial position was analysed by simple main effects and is summarised in Figure 9.6. This indicated no difference between the second-half word length conditions for either Spanish (all F

< 1.45) or English (all F < 3.64) at any serial position. A higher proportion of correct responses was present in Spanish than English at the short second-half word length condition for the fourth (F (1, 15) = 10.09, p < .01, means = 0.76 and 0.56 respectively) and fifth (F (1, 15) = 14.41, p < .01, means = 0.76 and 0.52 respectively) serial positions and at the third serial position of the long second-half word length condition (F (1,15) = 4.96, p < .05, means = 0.84 and 0.70 respectively). The presence of this second-order interaction was, therefore, attributable to a difference in performance between the languages and not the length of words in the second-half of the sequence.

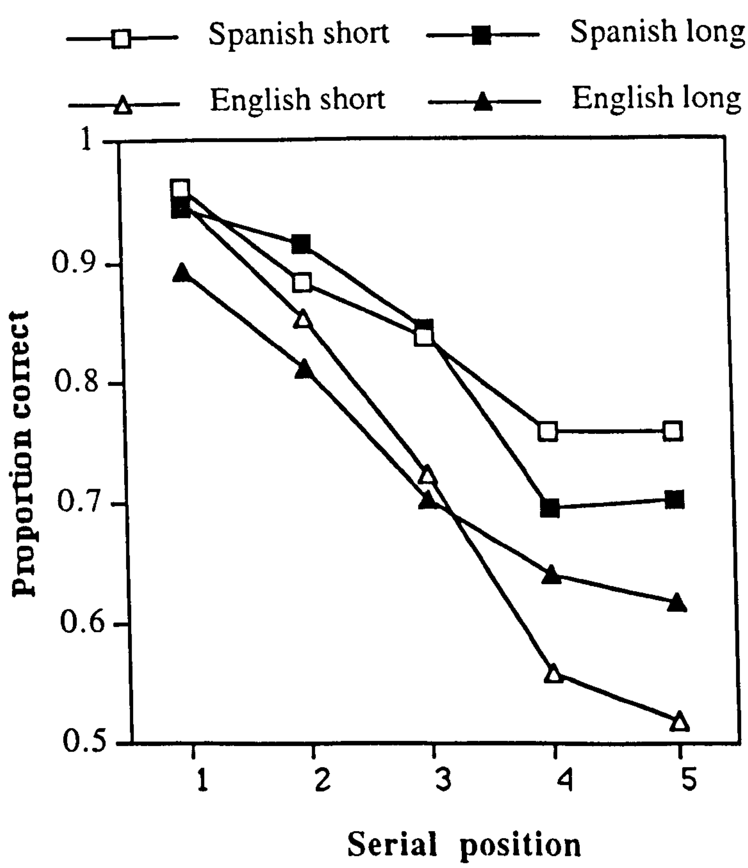

Figure 9.6: Mean proportion correct for the short and long second-half word length condition for Spanish and English as a function of serial position in the forward recall condition.

In short, the results of the forward recall direction data indicated an effect of first-half word length on immediate memory and, in this case, supported the output delay hypothesis although the effect was restricted to performance in Spanish.

Backward Recall

A corresponding analysis of the backward recall data revealed a main effect of language (F (1,15) = 7.98, $p < .05$) with a greater proportion of correct responses for Spanish than English (means = 0.79 and 0.72 per cent respectively), and a main effect of serial position (F (4,60) = 29.95, $p < .0001$) with a greater proportion of correct responses for the items presented in the last serial positions and, therefore, recalled first. The two-way interactions between language and first-half word length (F (1,15) = 6.19, $p < .05$) and language and serial position (F (4,60) = 2.76 $p < .05$) were reliable. None of the second- or third-order (F (4,60) = 1.34) interactions were reliable.

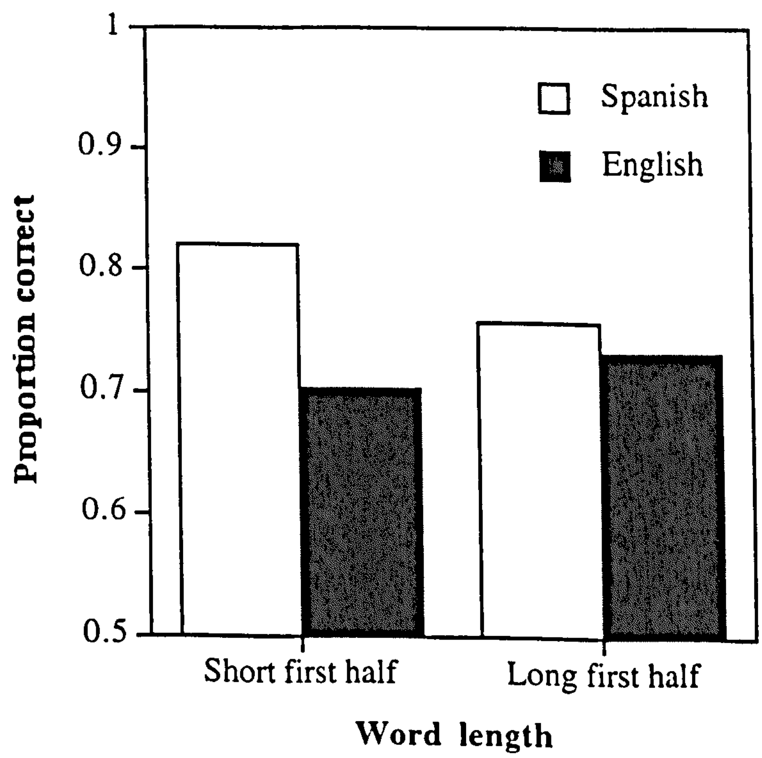

Figure 9.7: Mean proportion correct for the short and long first-half word length condition for Spanish and English in the backward recall condition.

The two-way interaction between language and first-half word length was analysed by simple main effects and is summarised in Figure 9.7. The results indicated that the difference between the short and long first-half word lengths was not reliable for English (F (1,15) = 0.55, means = 0.70 and 0.73 per cent respectively) or Spanish

($\underline{F}$ (1,15) = 2.36, means = 0.82 and 0.76 per cent). A language difference for the short first-half word length condition ($\underline{F}$ (1,15) = 10.752, $\underline{p}$ < .05) was present with a greater proportion of correct responses for Spanish than English (means = 0.82 and 0.70 per cent respectively) but not for the long first-half word length condition ($\underline{F}$ (1,15) = 0.51, means = 0.76 and 0.73 per cent respectively), hence the interaction term. The presence of this second-order interaction was, therefore, attributable to a language difference and not the effects of word length in the first-half of the sequence.

The interaction between the language and serial position factors was analysed by simple main effects and is summarised in Figure 9.8. The results indicated an effect of serial position for both Spanish ($\underline{F}$ (4,60) = 12.02, $\underline{p}$ < .0001) and English ($\underline{F}$ (4,60) = 18.73, $\underline{p}$ < .0001). The language difference between Spanish and English at the first ($\underline{F}$ (1,15) = 4.40, $\underline{p}$ = .056, means =0.78 and 0.66 respectively) and second ($\underline{F}$ (1,15) = 3.52, $\underline{p}$ = .08, means = 0.72 and 0.61 respectively) serial positions were marginal with a greater proportion of correct responses associated with the dominant language than the less dominant one.

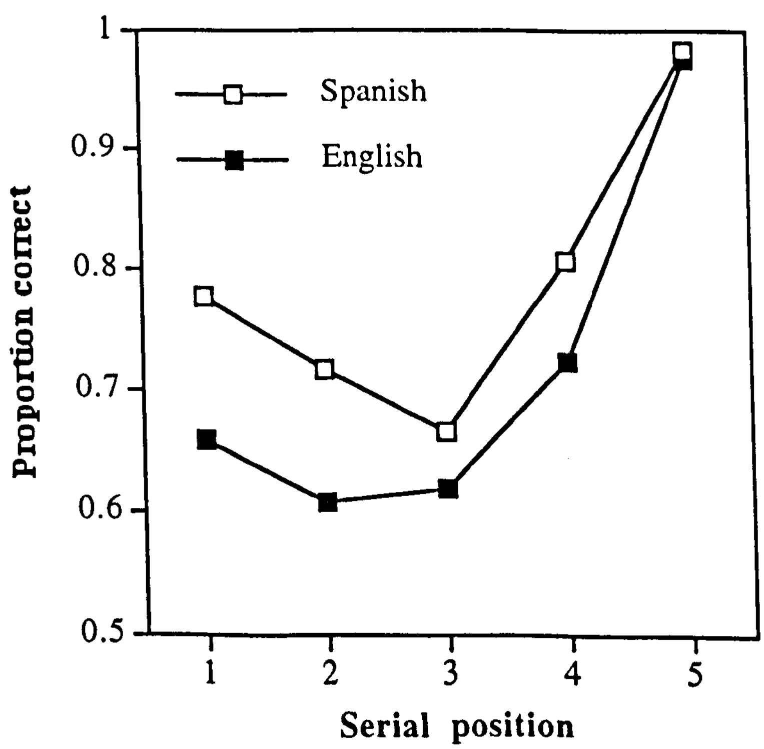

Figure 9.8: Mean proportion correct for Spanish and English words as a function of serial position in the backward recall condition.

To summarise, the present findings indicated that the first-half word length manipulation had an effect on the overall proportion of correct responses in the forward recall direction when performance was specified in the dominant language. Experiment 11, thus, replicated Cowan et al.'s (1992) finding of an effect of first-half word length on recall for subsequent items although this was restricted to forward recall and, then, only for Spanish.

Memory Decay

The rate of memory decay was calculated as described for Experiment 9. The linear regressions for the forward recall direction were described by $y = -0.228x + 0.98$ ($R^2 = 0.70$, $p < .05$) for the Spanish data and by $y = -0.214x + 0.93$ ($R^2 = 0.90$, $p < .01$) for the English data and are summarised in Figure 9.9. Inspection of the functions indicated that the intercept was higher for Spanish than English (although the difference was halved compared to the results of Experiment 10) and that the gradients were

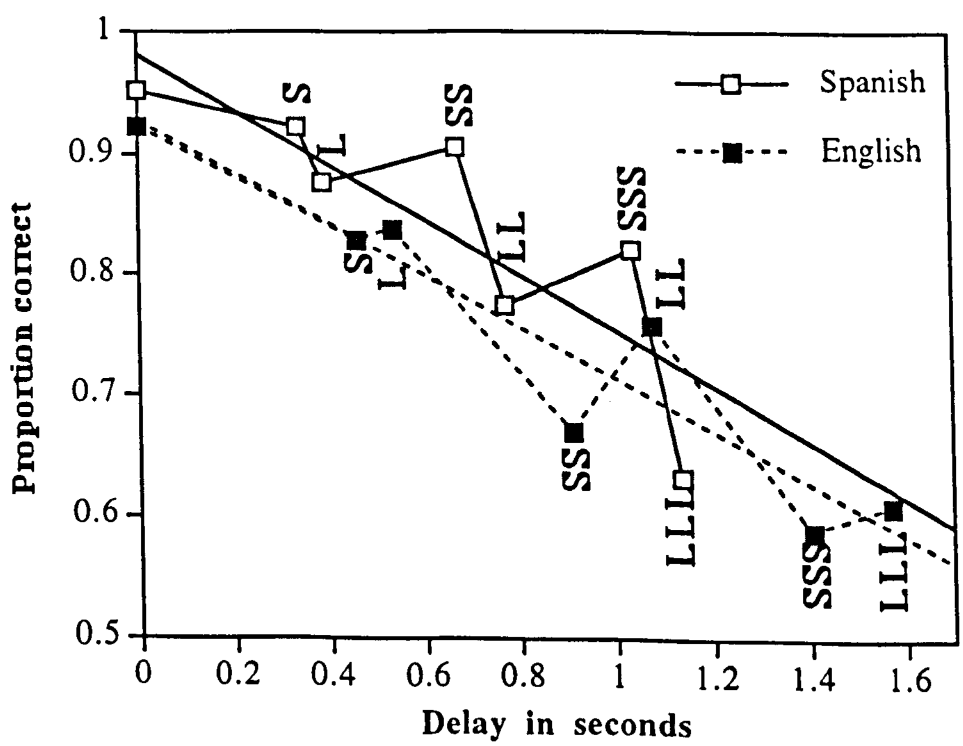

Figure 9.9: Mean proportion correct as a function of the estimated total of elapsed articulation time prior to the recall attempt and linear regressions in Spanish (solid line) and English (broken line) for forward recall.

broadly comparable (and almost identical to those of Experiment 10). In this case, however, the difference in the proportion of correct responses was not reliable (t = 1.54, p > .05, means = 0.95 and 0.92 respectively).

For the backward recall condition the fit to the Spanish data was described by the linear function $y = -0.290x + 0.98$ ($R^2 = 0.68$, $p < .05$) and by $y = -0.252x + 0.96$ ($R^2 = 0.81$, $p < .01$) for the English data and are summarised in Figure 9.10. The gradients for the Spanish and English data were comparable (although the difference between them was greater than for Experiment 10) and the intercepts for the Spanish and English functions differed by the narrowest of margins (0.02).

9.3.3: Discussion

When the frequency of the items approximated that of the words used by Cowan et al. (1992), an effect of first-half word length, and hence output delay, on recall was

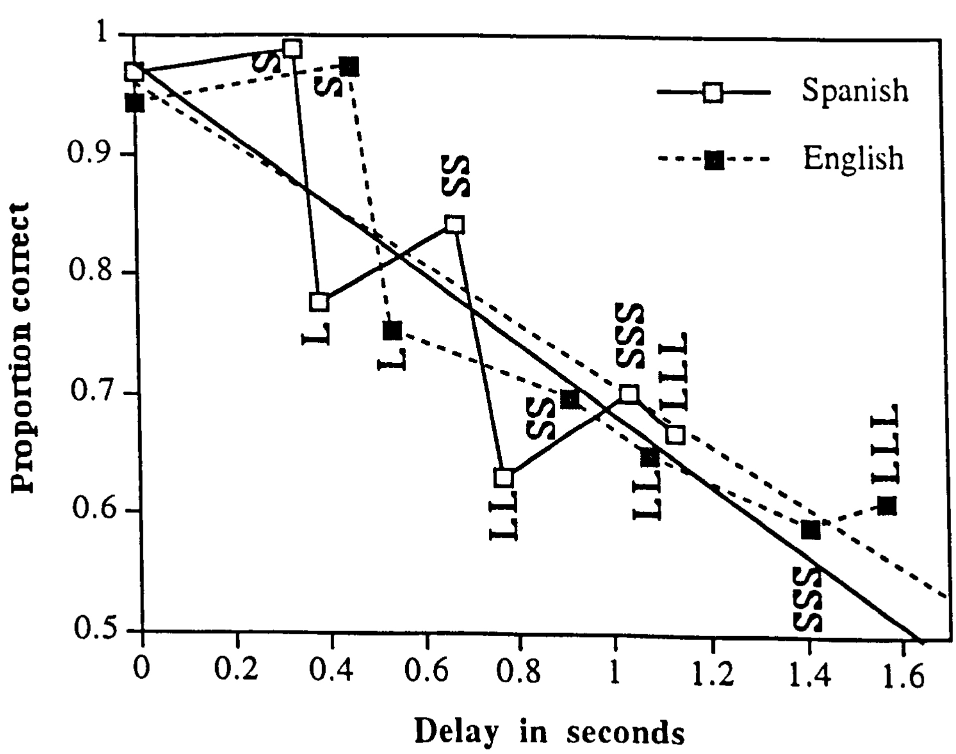

Figure 9.10: Mean proportion correct as a function of the estimated total of elapsed articulation time prior to the recall attempt and linear regressions in Spanish (solid line) and English (broken line) for backward recall.

present for Spanish in the forward recall task. The Cowan et al. (1992) findings, however, were not replicated perfectly as in the dominant language no effect of output time was present for the backward direction of recall. This may have been a consequence of the marginally higher frequency of items in the present study compared to those used by Cowan et al. (1992). Alternatively, a feature of the present design was that the word length manipulation for the backward recall task involved two items compared to three items for forward recall may have resulted in a lack of sensitivity to the effect of output delay when the direction of recall was reversed.

When performance was specified in English the word length manipulation had no effect in either recall direction. One explanation for the variation in outcome between the languages was that the short and long English items lacked equivalence in some respects. It is possible, for example, that the long-term representations for the English words were so weak (effectively making them nonwords) that subjects relied on the use of strategy to cope with the increased difficulty in recalling these low frequency items. This may have entailed the long words such as pineapple, tablespoon, and nursery being encoded as apple, table, and nurse in order to support recall making the word length manipulation less effective in English than Spanish.

The memory decay functions were similar to those of Experiment 1 in that for forward recall the y intercept was higher in Spanish than English (although, notably, the difference between the languages was halved), whereas they were almost identical in the case of backward recall.

Overall, the outcome of Experiment 11 supported the view that variation in output delay was an influential determinant of the word length effect for forward recall in the dominant language when the frequency of the items was low.

9.4: DISCUSSION OF EXPERIMENTS 10 & 11

The motivation for the present studies was to examine the role of output delay in mediating the bilingual word length effect. For bilinguals speech rate and, consequently, the rate of subvocal rehearsal is faster in the dominant than the less dominant language even when syllable length is matched. It was reasoned that the variation in speech rate between the languages could, plausibly, be an influential variable in determining the superior memory performance in the dominant language. The method employed by Cowan et al. (1992) was, therefore, applied to investigate the role of output delay in a task of immediate memory span between the dominant and less dominant languages of Spanish-English bilinguals.

The items in the Cowan et al. (1992) study consisted of low frequency words (approximately 1 per million). Words of similarly low frequency would be inappropriate for the purposes of the present investigation given the likelihood that bilinguals would be less familiar with low frequency items in the less dominant language. In order to maximise the chances of the material being processed equivalently between the languages high frequency words (approximately 255 per million) were used.

The findings of Experiment 10 indicated a greater proportion of correct responses in Spanish than English for forward recall. The manipulation of first-half word length, however, was of no consequence in determining either the relationship between the languages, or the overall proportion of correct responses. Instead, and quite unexpectedly, it was found that the word length of items in the second half of the sequence (the items recalled last) was crucial in determining the likelihood of recall accuracy. By contrast in the backward recall condition the length of words in the second half of the presentation sequence (and recalled last) determined the proportion of correct responses: although in this case no language differences were present.

These findings indicated that the word length of items in the second half of the output sequence was crucial in determining the pattern of recall and, thus, diverged from those of Cowan et al. (1992) in which the word length of the initially recalled items was the variable that moderated performance. The results of Experiment 10, thus, suggested that when items enjoyed strong long-term representations the effect of output delay in mediating recall performance was diminished to the point of exclusion.

Instead, the pattern of results was consistent with the view that performance was determined by the temporal limitations of the phonological loop.

Experiment 11, tested whether the absence of an effect of output delay on recall performance in Experiment 10 was a direct consequence of using high frequency words and presented items with frequencies closer to those of Cowan et al. (1992, approximately 10 per million). The results provided partial support for the view that output delay was an influential factor in mediating the effects of word length as the articulatory duration of items in the initial part of the sequence was critical in determining recall performance. The effect, however, was limited to forward recall in Spanish, whereas in the backward recall condition the word length manipulation had no effect on performance in either language.

The present findings would have been more conclusive had an effect of output delay been present for Spanish in the backward recall condition. Given the important processing differences that have been demonstrated between forward and backward recall (e.g., Farrand & Jones, 1996; Li & Lewandowsky; 1993, 1995), however, it is plausible that the word frequency of the items in Experiment 11 was sufficiently low for the effect of output delay to be manifest for forward but not backward recall. Alternatively, in the present studies definitions of the words in both Spanish and English were provided before the memory task, whereas Cowan et al. (1992) did not do so. It is possible, therefore, that in the Cowan et al. (1992) study familiarity with the items (e.g., hackle, coerce, and zygote) was so low as to occasion an exaggerated effect of the deleterious consequences on recall associated with output delay.

In Experiment 10, a long word sequence in Spanish took 1.74 seconds to articulate, whereas in Experiment 11, this took 1.86 seconds. In the first case, the total articulation time was below an estimated average capacity of the phonological loop (1.75 seconds), whereas in the second, this was marginally exceeded. It may be argued that the variation in articulation time between the present studies made discrete demands on the phonological loop and that this factor may have determined the opposing outcomes of output delay between Experiment 10 and 11. An explanation based on articulation time differences between the studies, however, does not account for the effect of second-half word length for English in Experiment 10 where articulation time for a long word sequence was 2.46 seconds. Instead, it seemed more plausible that the variation in the effects of output delay was due to the manipulation of word frequency and not differences in articulation time and a contingent effect on the rate of subvocal rehearsal.

Avons et al. (1994) have argued that the word length effect may not be accounted for solely in terms of subvocal rehearsal and that part, if not all, of the effect must be attributed to output delay resulting from either trace decay or temporal capacity restrictions. The present findings indicated that output delay, and thus the word length effect, occurred a function of word frequency. When word frequency was high temporal capacity was an influential factor in mediating recall performance, whereas when word frequency was low, recall was mediated by the rate of decay from the phonological store. The nature of the processes and the precise parameters by which resistance to the effects of output delay were moderated were not capable of being identified in the present study, however, an explanation in terms of varying redintegration efficiency seemed plausible.

We now return to the finding in Experiment 10 that indicated a difference in the proportion of correct responses between Spanish and English for forward but not backward recall. As has already been stated, this suggested that factors related to articulation rate were of no consequence in mediating performance when recall was specified in reverse order. Although the word frequency for the items between the languages was equivalent, it was reasonable to assume that the long-term representations for the items were stronger in Spanish than English (the former being the dominant language). If this was so, it could be argued that the strength of long term representations was an equally unimportant factor in the backward recall task.

Support for this notion may be found in a study of the effects of word frequency on short-term memory for monolinguals by Hulme, Schweickert, Brown, Martin, and Stuart (in press). These authors reported that, independent of speech rate, forward recall for high frequency words was greater than for low frequency ones. For backward recall, however, word frequency had no effect on memory performance when the articulation time was controlled. Hulme et al. (in press) considered the possibility that in backward recall tasks, retrieval mechanisms may involve the use of semantic strategies, whereas greater dependence is placed upon phonological rehearsal in forward recall.

Although further investigation is, clearly, required before firm conclusions are made, the present paradigm may prove useful in exploring the nature of redintegrative process more closely. Studies in which the strength of phonological and semantic long-term memory representations are manipulated and the consequent effects on recall performance examined could be informative. In terms of bilingual information processing, a prospective line of enquiry involving similar manipulations could ascertain the relative contributions of phonological and semantic long term knowledge between the dominant and less-dominant languages.

In short, it was concluded that the effects of output delay should not be assessed without consideration of the effects of word frequency. When the frequency of words was high and the long-term representations strong (as in the case of Spanish), no evidence in support the view that word length effects were solely mediated by variation in output time was obtained. Instead, the present findings suggested that for high frequency items, word length effects were a consequence of the temporal limitations associated with the phonological loop.

Although no firm support was found for the view that variation in output delay between the languages exclusively mediated the bilingual word length effect, the present evidence, suggested that a slower articulation during recall decreased the likelihood of weak long-term representations being recalled before decaying irretrievably. It may reasonably be inferred, therefore, that under specific circumstances, bilingual word length effects may be due in part to slower articulation time during output.

The present findings, thus, moderated those of Cowan et al. (1992) and indicated that the effects of output delay on memory performance for visually presented material were a function of factors related to word frequency and, hence, the strength of long-term representation. Overall, the results reported here were consistent with the view that short-term memory is supported by a redintegrative process that assists in the pattern completion of decaying traces as proposed by Hulme et al. (1995) and Brown and Hulme (1995).

Chapter 10
Grand Discussion

Much of the discussion pertaining to the logic and rationale that motivated the individual experiments presented in this thesis has been ongoing and will not be rehearsed here. Instead, this chapter provided an account of the progression of the studies as well as an attempt at a synthesis and consolidation of the main findings in order to arrive at a set of conclusions in relation to the general research question.

The enterprise began with an examination of the relatively scant literature that had previously examined the bilingual digit span effect. The one consistent finding that could be determined with any degree of certainty from these studies was the reassuring indication that the bilingual digit span effect existed. The only sensible conclusion in terms of the factors that mediated the between-language difference in memory span capacity, however, was that both the methodology as well the variation in findings across these studies was high.

A natural starting point, then, was to attempt to provide a basis upon which to conclude whether the bilingual digit span effect was moderated by a variation in word length and the rate of subvocal rehearsal (Ellis & Hennelly, 1980), by factors related to mother tongue superiority (da Costa Pinto, 1991), or the language of schooling (Naveh-Benjamin & Ayres, 1986). It soon became apparent that to ask this initial, relatively simple, question was to underestimate the complexity of the phenomenon under examination quite severely and consequently the series of studies that constituted this thesis was spawned.

In Experiment 1, three hypotheses that claimed to account for the variation in bilingual digit span were pitted against each other and the degree to which digit span performance was associated with the language of the home and language of the school examined. The linguistic characteristics of Finnish society allowed the orthogonal variation of these factors with a level of precision that had been unachievable in previous studies.

The findings of Experiment 1 suggested that digit span tended toward being greater in the language of schooling rather than the language of the home (or mother tongue). A result predicted by Naveh-Benjamin and Ayres (1986) on the basis that a greater level of practice in counting and computation and general familiarity with digits were likely to be associated with the language in which schooling was received. A more detailed analysis according to bilingual type, however, indicated that although the language of schooling was an influential determinant of bilingual digit span performance it did not account for performance by the compound bilingual types (SF & FS) where Finnish and Swedish digit spans were equivalent.

A corresponding analysis of the numeral reading data indicated that this measure reliably predicted performance on the digit span task. Moreover, articulatory suppression eliminated the language difference in numeral span for the compound bilingual types (SS & FF). It was, thus, concluded that the findings of Experiment 1 were broadly consistent with the view that the language difference in bilingual digit span was modulated by the rate of subvocal rehearsal and the functioning of the phonological loop component of working memory as previously suggested by Ellis and Hennelly (1980) and Chincotta and Hoosain (1995).

The post hoc analysis of the data from a sample of balanced, compound bilinguals selected on the basis of self-ratings indicated that between-language performance on the numeral reading task was equivalent. Performance on the digit span task, however, varied according to bilingual type. The Swedish mother tongue-Finnish schooled bilinguals (SFS) had equivalent digit spans, whereas their Finnish mother tongue-Swedish schooled counterparts (FSS) had a larger digit span in Swedish than Finnish. Thus, for this group of individuals numeral reading time did not predict performance on the digit span task. The pattern of findings, therefore, suggested that neither the language of schooling nor the speech rate (word length) factors could account for the complete range of bilingual digit span performance.

It was clear that the limitations of this initial study imposed important constraints on the interpretation of the findings and the conclusions that could be drawn. The questions raised in Experiment 1, nevertheless, served as a basis upon which to plan subsequent studies and to examine related issues further.

Firstly, although the finding that numeral reading time predicted numeral span, was interpreted as support for the view that speech rate was an influential mediator of the bilingual digit span effect, the question remained as to precisely what the numeral reading task indexed. The findings of the digit word reading pilot study, on the other hand, indicated that all groups, regardless of bilingual type, consistently read the items faster in Swedish than Finnish. More important, within-language performance did not vary across bilingual type for either Swedish of Finnish. The reading time estimates of digit word length, thus, varied as a function of digit representation with digit word reading time being the more stable of the two indices in terms of consistent performance across the groups. The absence of variation as a function of bilingual type on the digit word reading task raised the question as to whether the numeral reading task was a measure of actual differences in the spoken duration for digit names between languages. This finding suggested that digit word reading indexed what was an intuitive word length advantage (as estimated by syllable count) for Swedish digits over Finnish ones.

It would, of course, have been nonsensical to compare reading time measures for one representation of digits with memory span performance for another. Nevertheless, the findings of the digit word reading task were of some value in that they raised questions with regard to the most appropriate method of estimating speech rate and word length. Any conclusion as to the factors that determined bilingual memory capacity would, thus, have to be deferred until a clearer understanding of the relationship between the various speech rate estimates and the power of these measures in predicting digit span was obtained.

Secondly, the post hoc analysis of the sample of balanced bilinguals indicated that performance on the numeral reading task did not predict the range of performance on the digit span task: although the degree of association between the variables was moderate and significant (Finnish = - 0.71 and Swedish = - 0.63). Moreover, the finding that the FSS group had a larger digit span in Swedish, whereas the SFS group showed no difference between the languages suggested that the differences in word length between the languages attenuated the bias in favour of superior performance in the language of schooling. Thus, although the impact of the word length variable seemed to underlie the bilingual digit span effect, it could not be dissociated from the effect of practice or familiarity with digits associated with schooling.

Thirdly, the results of the digit word reading task suggested that bilingual digit span performance varied depending upon whether digits were represented as numerals or digit words. That is, if the bilingual digit span effect was mediated by word length and the rate of subvocal rehearsal, it seemed plausible that the consistently shorter reading time for Swedish digit words obtained by all the bilingual types could occasion a larger digit word span for Swedish and a numeral span that varied according to bilingual type. The variation in reading time measures, however, indicated that these estimates of speech rate were not independent of factors related to the recognition and naming speed of the stimuli and, thus, not exclusively influenced by differences in the actual articulatory duration for digit names. Nevertheless, it seemed logical to suppose that the processes that mediated the pattern of performance in the reading tasks would also be present in the digit span tasks.

These separate, yet related, lines of enquiry were pursued as a consequence of the various inconsistencies outlined above and are discussed more fully in the following sections. Consideration of these issues was organised in sections as follows. Section 10.1 examines the problems involved in obtaining appropriate estimates of bilingual speech rate. In addition, the question as to what these different methods of speech rate estimation actually indexed was discussed. The following section (10.2) focuses on the effect of non phonological factors in determining bilingual memory span effects and describes the attempt to examine the role of long-term memory representations through the manipulation of lexicality. Section 10.3 discusses the numeral advantage effect and the attempts to uncover the underlying processes that mediated the superior recall of numerals compared to digit words. In Section 10.4, the contribution of factors related to item identification and the speed of perceptual processing and a putative involvement of visuo-spatial short-term memory in modulating the numeral advantage effect is examined. Section 10.5 addresses the question as to the role of output processes on immediate recall and a tentative attempt to synthesise the range of findings in presented in this thesis. Finally, a theoretically motivated consideration of the effect of articulatory suppression on bilingual digit span is presented in Section 10.6.

10.1: Speech Rate Estimation in Bilinguals

10.1.1: What Does Numeral Reading Time Index?

Although performance on numeral reading tasks has generally been accepted as an index of language differences in word length for digits (Ellis & Hennelly, 1980; da Costa Pinto, 1991; Chincotta & Hoosain, 1995), the findings of the digit word reading task presented in Experiment 1 raised the possibility that numeral reading was sensitive to variables other than actual spoken duration (or word length). Of course, it was reasonable to assume that, to some extent, all measures of speech rate involved processes requiring recognition (whether auditory or visual) and the planning of articulatory gestures in preparation for speech output. These factors are necessarily present in all estimates of word length and indices of subvocal rehearsal rate. In the case of numerals, however, it was considered likely that the absence of lexical support and the language-neutral nature of the stimuli made additional cognitive demands on bilinguals when performance was specified in the less-dominant language. It was hypothesised, therefore, that extra cognitive demands due to possible Stroop-type interference from the dominant language made the numeral reading task qualitatively different to articulation and digit word reading tasks where additional phonological and lexical support respectively were present. For these reasons, it was speculated that the numeral reading task produced measures of speech rate that were sensitive to the level of relative proficiency between the bilingual's languages rather than actual spoken duration.

In order to examine this notion, the power of three estimates of speech rate, articulation, numeral and digit word reading, in predicting bilingual digit span was compared in Experiment 2. A study of the association between various indices of processing in relation to memory span (Hitch et al., 1989) concluded that articulation time was a more appropriate index of subvocal rehearsal rate than estimates involving reading. In Experiment 2 memory span was measured in the auditory modality, therefore, if the bilingual digit span effect was modulated exclusively by the rate of subvocal rehearsal, articulation time should, theoretically, have been the most reliable predictor of the language relationship in the memory span task.

The findings of Experiment 2, however, indicated that articulation time (a speech rate estimate independent of visual recognition), did not predict the equivalence in Finnish and Swedish auditory digit span for nine grades of Finnish mother tongue-Swedish schooled children. This finding suggested that auditory bilingual digit span was not mediated by factors related to word length and the rate of subvocal rehearsal. This was not to suggest, however, that articulation time was unrelated to auditory digit span as moderate and reliable correlations between the factors were present (ranging from - 0.34 and - 0.47).

The between-group comparisons of speech estimates in Swedish indicated that the FS group performed equivalently to their Swedish-dominant peers. This suggested that, as far as performance on the speech tasks was concerned, receiving schooling in a language other than the mother tongue did not disadvantage the FS group compared to native speakers of the language of school instruction. The FS bilingual type, however, had a consistently lower Swedish auditory digit span that the SS bilingual type. This was an added indication that speech rate (however estimated) did not account for the full range of performance on the memory span task.

The correlational analysis of the three speech time estimates indicated that articulation time and numeral reading time were not differentially correlated with digit span, whereas digit word and numeral reading time were differentially correlated in three out of four possible cases. Although the findings of Experiment 2 did not support the hypothesis that numeral reading indexed different processes to the articulation time estimate, they did suggest that the numeral and digit word reading estimates measured different cognitive processes. Paradoxically, although digit word reading time correlated to a lower degree than numeral reading time, it was the former speech rate estimate that best predicted performance on the memory span task.

Although the findings of Experiment 2 highlighted the inadequacy of word length and subvocal rehearsal rate explanations of the bilingual digit span effect, unfortunately, the results were less conclusive insofar as providing an answer as to what the numeral reading task actually indexed. That is, it could not be ascertained whether numeral reading time was an index of relative language fluency in bilinguals or an accurate estimate of cross-linguistic differences in the articulatory duration of digits. A major limitation of this study was the impossibility of assessing whether overall performance by the FS bilinguals (a group with a balanced language background) was mediated by a language of schooling effect, a word length advantage for Swedish digit names relative to Finnish ones, or an interaction between the factors. Moreover, the complexity of the intercorrelations between the distinct estimates of speech rate and memory span was likely to have added a large amount of noise to the data and may have masked the true nature of the relationship between numeral reading and articulation time.

Experiment 5, therefore, attempted to address the shortcomings of Experiment 2 identified above. In this study, the effects of familiarity and practice were controlled more stringently by selecting two Finnish-Swedish constant bilingual types as described in Experiment 1 (i.e., FF & SS). These individuals had received schooling in their respective mother tongues and were, thus, Finnish- and Swedish-dominant respectively. Under these circumstances, a putative greater level of familiarity and proficiency in the mother tongue eliminated the potential confound between the languages of schooling and the home. Both groups had studied their respective second languages at school for approximately 9 years although, in the case of SS, added reinforcement in Finnish (the dominant language in Finland) was likely to result in a near-to-native fluency in this language (see Experiment 1). It was reasoned that a comparison of performance between these types would provide a clearer indication of differences in processing between articulation and numeral reading tasks and, thus, allowed a more detailed examination of whether the articulation and numeral reading tasks made discrete cognitive demands.

Direct estimates of numeral processing were obtained by applying the technique of monitoring eye movements during the reading of Finnish and Swedish sentences in which the target stimuli were embedded. The requirement that the stimuli were read aloud was essential to ensure that processing was conducted in the specified language. The on-line measurement of reading is an ecologically valid indication of the cognitive processes required for the recognition of the stimuli and assumes that an eye fixation is maintained on an item until processing is completed (Underwood & Batt, 1996). Previous eye movement studies of number processing in monolinguals (e.g., Brysbaert, 1995) found that fixation durations on numeral stimuli varied as a function of the syllable length of number names: a finding taken as evidence for phonological coding during reading.

The question addressed in Experiment 5, then, was whether for bilinguals the processing of numerals was mediated by the syllable length or articulatory duration of the stimuli or whether additional cognitive loads associated with post-recognition processes such as phonological recoding, lexical search and the compilation of articulatory output codes in the less-dominant language.

The results of the eye movement study showed that gaze duration was shorter in the respective dominant languages of the FF and SS bilinguals, whereas the results of articulation task indicated that articulation time was consistently shorter in Swedish than Finnish for both bilingual groups regardless of language dominance. The results of the numeral reading task indicated that performance varied as a function of language dominance and, thus, mirrored performance on the eye-tracking task. Taken together, these findings suggested that articulation time was a measure of word length that was relatively insensitive to the language dominance of the FF bilingual type, whereas both numeral reading time and numeral gaze duration provided measures of performance that followed the pattern of language dominance of each bilingual group. On the basis of these results, it was argued that the numeral reading task was affected by retrieval processes that were largely independent of articulatory duration and that this measure of speech rate was sensitive to the relative level of proficiency between the languages.

If the conclusion that numeral reading time is an index of the relative degree of fluency between the bilingual's languages rather than either an accurate estimate of the actual articulatory duration of the items is accepted, this gives rise to two issues. Firstly, how does this notion impinge upon the conclusions regarding the role of word length and speech rate made in previous bilingual digit span studies? Secondly, to what degree could the relative fluency with numerals, as indexed by the numeral reading task, account for performance across the range of bilingual digit span studies?

The first point may be addressed in a relatively straightforward manner. If it is accepted that the numeral reading task was contaminated by factors related to the proficiency for numerals between languages, severe restrictions are thereby placed on the conclusions that may be drawn in respect of the relationship between speech rate (as estimated by this measure) and bilingual memory span for digits. This was best illustrated by reference to the Ellis and Hennelly study (1980) in which numeral reading measures were used a basis for confirming a hypothesised shorter word length in English than Welsh. The finding that auditory digit span was greater in English than Welsh was, thus, taken as support for the view that the bilingual digit span effect was mediated by differences in the digit word length between the languages. Similarly, da Costa Pinto (1991) found that numeral reading time predicted a larger auditory digit span in Portuguese than English (although in this case, performance on the memory span task was also predicted by a digit word reading task).

As has been argued, however, the present evidence suggested that numeral reading time provides an indication of language dominance rather than an appropriate estimate of bilingual differences in digit word length and the rate of subvocal rehearsal. It is not necessary to labour the point that the assumption that numeral reading is an adequate index of word length in previous studies was fundamentally flawed. Moreover, the absence of appropriate measures of speech rate (articulation time) in relation to the auditory memory span task, therefore, made the findings of these studies inconclusive.

The points discussed above with respect to the sensitivity of numeral reading tasks to language proficiency, thus, required the reinterpretation of the findings of Experiment 1. In this study, the relationship between numeral reading time and numeral memory span and the association between performance and the language of schooling was taken as evidence with which to propound the view that the bilingual digit span effect was modulated by speech rate and phonological loop functioning: a view reinforced by the finding that articulatory suppression erased the language difference between Finnish and Swedish for the FF and SS bilingual types. In the light of the findings of Experiment 5, however, it seemed likely that the association between memory span performance and language of schooling was mediated by a higher level of proficiency for numerals in the language of the school. These discrete levels of proficiency for numerals were, naturally, reflected in the numeral reading time measure. This is not to say, however, that the actual spoken duration of digits was a factor without influence as the findings of the post hoc analysis of the sample of balanced bilinguals indicated a degree of interplay between articulation time and familiarity with numerals. Rather, the position adopted here is that the cognitive processes involved in the recognition of numeral stimuli occasioned estimates of word length and speech rate that masked the actual articulation duration of the items in question and were, consequently, more likely to index the relative degree of proficiency with numerals.

This view was further supported by the findings of the digit word reading task that, as a consequence of additional lexical support, yielded distinct approximations of the articulatory duration of Finnish and Swedish digits.

It was proposed, therefore, that the interpretation of the relationship between numeral reading time and numeral span as a direct consequence of word length and, hence, speech rate was fundamentally incorrect. Instead, it seemed more plausible that the findings of Experiment 1 demonstrated the effects of familiarity and stronger long-term memory representations for numerals in the language in which an overwhelmingly greater degree of exposure and practice with these stimuli was experienced. Once this notion was accepted, it became relatively unsurprising that numeral reading time predicted numeral memory span so reliably.

This explanation of the findings of Experiment 1, however, failed to account for the effect of articulatory suppression in eliminating the memory span differential between Finnish and Swedish. According to working memory theory, the elimination of memory span differences under articulatory suppression is interpreted as evidence of phonological loop involvement and the effect of word length. In order to sustain the position that the pattern of results in Experiment 1 did not reflect such processes it was necessary to account for the pattern of results under articulatory suppression (this was done in Section 10.6). Before doing so, however, other issues arising from the view that numeral reading time is an index of relative language fluency were addressed.

10.1.2: Language Proficiency and Bilingual Digit Span

The above discussion raised the question as to whether the relative level of fluency for digits, as indexed by numeral reading time, could account for the range of performance in bilingual digit span studies. As has been stated, the findings of both the Ellis & Hennelly (1980) and da Costa Pinto (1991) studies may be explained in terms of a higher level of proficiency for digits in the language in which numeral reading time was shorter. It was, thus, contended that in these studies bilingual word length differences were erroneously established using an estimate of speech rate that was heavily influenced by language fluency. If this view is accepted, it is relatively unsurprising that bilinguals obtain larger spans in the language in which proficiency with numerals, as indexed by numeral reading time, was highest. It was one thing to argue that bilingual numeral reading estimates of word length are heavily contaminated by the language of greater proficiency for numerals and quite another, however, to claim that the bilingual's digit span will always be larger in the language in which numeral reading time is shortest. The only claim made here is that numeral reading indexes proficiency with numerals rather than word length per se, and that it is language fluency that is, arguably, the most influential mediator of performance in numeral reading tasks.

As far as the findings of previous bilingual digit span studies that have estimated speech rate on the basis of numeral reading tasks were concerned, the findings were clear: larger auditory digit spans were consistently associated with the language in which numeral reading time was shorter. This pattern of findings was interpreted as support for the suggestion that bilinguals are likely to obtain larger auditory modality in the language in which verbal proficiency for numerals (as estimated by numeral reading time) is greatest. By extension, if it is accepted that the processing of numerals in the less-dominant language makes extra cognitive demands, owing to the unavailability of lexical support and Stroop-type interference arising from the language neutral status of the stimuli, the findings that numeral spans are larger in the language in which shorter numeral reading times are obtained is relatively unsurprising.

In the Chincotta and Hoosain (1995) study, for example, speech rate was estimated in manner that was appropriate in relation to the memory span task (i.e., numeral reading and numeral span). Here too, numeral reading time was found to be a consistent predictor of numeral span performance for a total of seven bilingual types and three language pairings. Moreover, although in the Chincotta and Hoosain (1995) study, shorter numeral reading time in English was obtained by a sample of bilinguals that self-rated greater proficiency in Spanish, these subjects received schooling in English and were, thus, likely to be relatively more fluent with numerals in this language than in Spanish. Similarly, Chinese-English bilinguals in the Chincotta and Hoosain (1995) study obtained a shorter numeral reading times and a larger numeral span for Chinese, the language of primary schooling of the subjects, in this case, however, a greater proficiency for Chinese digits was confounded with a shorter word length for digits in the same language (Hoosain, 1984).

A consistent trend in the findings of the above-cited bilingual digit span studies, then, was that a larger memory span is associated with a shorter numeral reading time in both the auditory and visual modalities. This pattern of findings was supported by the experiments reported in this thesis, but not without exception. In Experiments 6 and 7, and 9, for example, the relationship between numeral reading and numeral span was observed, whereas in Experiments 5 a marginally greater numeral span was present in the language in which numeral reading time was shorter. In Experiment 8, on the other hand, despite a shorter numeral reading time for Spanish than English, this group of bilinguals obtained equivalent numeral spans between the languages: although the trend was in the right direction.

Insofar as the results of Experiment 8 were concerned, an explanation of the absence of a bilingual digit span effect for the numeral stimuli was that the majority of the subjects in this study (75 per cent) were Arts and Business students, whereas in Experiments 6 and 7 the number of Arts and Science students was equivalent. It seemed reasonable to suggest that Arts students would have a generally lower level of familiarity with numeral representations of digits and, arguably, a greater familiarity with digit word representations of digits than their Science-trained equivalents. It was plausible that these factors impinged upon performance and attenuated the numeral advantage effect reaching statistical significance.

Perhaps the most interesting findings in terms of establishing the effect of language proficiency for numerals on bilingual digit span performance were obtained in Experiment 2. The combined analysis of variance indicated that numeral reading time was the only speech rate estimate that consistently predicted the equivalence between Finnish and Swedish auditory digit span task for the FS bilingual type. This finding supported the view that numeral reading time was a reliable predictor of both auditory and visual bilingual digit spans: it will be recalled that articulation time was shorter in Swedish than Finnish. When the data were analysed separately according to bilingual type, however, the results suggested that digit word reading time was equivalent between the languages, whereas numeral time was marginally (64 msec/item), but reliably, shorter in Swedish than Finnish.

The finding that the combined and separate analyses of numeral and digit word reading time indicated different outcomes in terms of the relationship between Finnish and Swedish performance, unfortunately, made the results of this study inconclusive. Nevertheless, if the results of the combined analyses of the data are accepted as a veridical account of the data, the finding that for the FS group articulation time was shorter for Swedish than Finnish in 8 of the 9 school grades supported the view that numeral reading time indexed fluency rather than actual spoken duration and the rate of subvocal rehearsal.

10.1.3: What Does Articulation Time Index?

The issues discussed so far questioned what articulation time actually indexes. Brown and Hulme (1995) have pointed out that the evidence for a link between speech rate and memory span is largely correlational. Correlational associations between these factors, thus, cannot be interpreted as definitive support for a causal role of subvocal rehearsal in mediating the bilingual digit span effect as this estimate of speech rate is likely to be confounded with factors other than actual word length. It was reasonable to suggest that, in the case of bilinguals, all methods of speech rate estimation are likely to be affected by factors related to familiarity and proficiency to a greater or lesser degree. Experiment 2, tested the notion that three distinct methods of estimating speech rate indexed different cognitive processes. Although the correlational analysis failed to demonstrate conclusively that articulation, digit reading, and numeral time were differentially associated with auditory digit span, the finding that numeral and digit word reading time were associated to different degrees in three out of four possible cases provided partial support for the initial hypothesis.

One obvious explanation of the intercorrelations among the three measures of speech time was that a substantial part of the variance was shared between them. It seemed reasonable to suggest that familiarity and word length were two factors likely to share a substantial amount of common variance. The argument that numeral reading time estimates of speech rate are contaminated by interference from the dominant language when performance is specified in the less-dominant language has been extensively elaborated in the proceeding sections and will not be rehearsed here. It was interesting, however, that numeral reading time and articulation time were correlated to equivalent degrees with memory span. This could reasonably be interpreted as an indication that articulation time was also sensitive to the relative level of language proficiency.

The evidence from the overall analysis in Experiment 2 also suggested that digit word reading time was similarly affected by fluency and familiarity. Note, for example, that the magnitude of the difference between Finnish and Swedish reading time for the FS bilingual type decreased as a function of school grade, whereas the corresponding magnitude of the difference for the articulation time estimate remained relatively constant. It seemed logical to suppose that, particularly when the performance of schoolchildren is examined, reading skills in the language of schooling are likely to develop at a faster rate than in the language of the home.

The evidence discussed so far suggested that articulation time is both the more stable and the more appropriate estimate of actual spoken duration and, hence, the rate of subvocal rehearsal. In this sense, stability was defined as a reduction in the likelihood that measures of performance are affected by familiarity and a consequent, increased sensitivity to the linguistic features of the items such as syllable length. Although the limitations of using syllable length as a metric of word length are obvious (Baddeley et al., 1984;,Hoosain, 1984), nevertheless, this gross measure of spoken duration is a useful means of confirming approximate differences between languages.

Syllable counts are likely to be more useful in providing a gross approximation of the variation in spoken duration between languages when the difference between the pairings is relatively greater, as in the case of Finnish and Swedish (2.33 and 1.11 syllables per digit respectively), than when the differences are relatively shorter, as in the case of English and Spanish (1.11 and 1.66 syllables per digit respectively).

In Experiment 5, for example, Finnish-dominant bilinguals, had a shorter articulation time in Swedish than Finnish despite a relatively low level of proficiency in Swedish. This finding was, thus, in keeping with the gross approximation of word length differences between Finnish and Swedish digits according to syllable count. These Finnish-dominant subjects, however, did not perform at level equivalent to Swedish native speakers when performance was specified in the less dominant language. So, although articulation time was sensitive to syllable length, it was nevertheless, also naturally affected by familiarity.

In addition, the findings of Elliot (1992) supported the view propounded here in that, although sensitive to the surface linguistic features of the items in question, articulation time cannot be considered a familiarity-free index of word length. This was best demonstrated by the contrasting the performance of English-dominant, English-Mandarin and Mandarin-dominant, Mandarin-English bilinguals in Elliot's (1992) study. It will be recalled that both groups had a shorter articulation time in Mandarin than English (a finding consistent with a greater number of syllables in English than Mandarin). The results of the auditory digit span task, however, showed that the English-dominant group had an equivalent memory span between the languages, whereas the Mandarin-dominant group had a larger memory span in Mandarin. On the basis of these findings, Elliot (1995) suggested that although articulation time is relatively less sensitive to the effects of familiarity than measures requiring the recognition of print, the effects of familiarity are nevertheless manifest in memory span tasks.

On the basis of the above evidence, it was concluded that articulation time estimates of word length, although recognition-free in visual terms, was affected by factors related to fluency and familiarity. Thus, although articulation time is the most appropriate method of establishing differences in spoken duration between languages, it should not be assumed that such estimates are independent of the effects of language dominance.

The argument that the three estimates of bilingual speech rate performance used in this thesis were likely to be contaminated by factors related to fluency and familiarity fundamentally questioned the view that bilingual digit span effects are moderated by the relative word length of digit names between languages. In addition, the task of evaluating the independent contribution of actual spoken duration and subvocal rehearsal to memory span appeared insurmountable.

10.2: The Role of Long-Term Memory Representations

The evidence discussed so far, suggested that a simple working memory explanation of the relationship between speech rate and memory span did not account for the full range of findings in previous bilingual digit span studies or those presented in this thesis. The contamination of speech rate estimates involving both articulation and reading by familiarity effects made the interpretation of the relationship between subvocal rehearsal rate and memory capacity postulated by working memory theory difficult. A number of possible solutions to this dilemma were considered.

10.2.1: The Manipulation of Lexicality

It was reasoned that one way to identify the relative impact of speech rate and familiarity or the relative strength of long-term memory representations upon bilingual memory span was to adopt the Hulme et al. (1991) paradigm and manipulate of the lexicality of items (i.e., words versus nonwords). This experimental design allowed the examination of the independent effects of articulation time and the strength of long-term memory representation on memory span. In this study, the use of non digit stimuli circumvented the problems associated with the use of an unrepresentative set of highly over learned items. Furthermore, it allowed a stricter control over the differences in word length between languages that are inevitably present when bilingual functioning is measured using digits.

It was argued in the preceding section that articulation time estimates of speech rate, although less sensitive to the effects of familiarity than estimates involving the recognition of print, are, nevertheless, likely to be influenced by factors related to proficiency. Given the problems associated with the contamination of the familiarity factor on measures articulation time, closer attention to detail was required to determine the level of performance between the languages in relation to native speakers.

The Experiments presented in Chapter 4, were a significant departure from previous studies in that articulation time performance by the target bilingual group (FS) was compared to that of native speakers in Finnish and Swedish (SS and FF). These controls were an effective means of estimating whether the relationship between articulation time and memory span was influenced by relative levels of verbal fluency between the languages. Although seldom a feature of bilingual studies, it was reasoned that such controls would allow a greater certainty in evaluating the effects of familiarity on articulation time. This, in turn, allowed firmer conclusions to be made with regard to the role of speech rate in determining bilingual memory span.

The findings of Experiment 3 indicated that for the FS bilingual type, articulation time was shorter in Finnish than Swedish. More important, however, the target bilingual type articulated Finnish words at an equivalent rate to the Finnish-dominant group, and articulated Swedish words at an equivalent rate to the Swedish-dominant group. This pattern of findings, therefore, showed that for the FS bilingual type articulation time was equivalent to native speaker performance in each language. In addition, the finding that the relationship between the languages for the articulation time task varied as a function of language dominance supported the view that speech time estimates that did not require the recognition of print were affected by fluency and familiarity.

The results of the memory span task showed that the FS group had equivalent memory spans in Finnish and Swedish, thus, articulation time did not predict the relationship between the languages for this bilingual type. As expected, for the remaining bilingual types, articulation time was a reliable predictor of the between-language relationship for the memory span task. As has already been stated, it was not possible interpret these findings as evidence in support of a causal effect of speech rate on memory span. Instead, it seemed more reasonable to conclude that although articulation time predicted the between-language outcome on the memory span task for the SS and FF groups, it was likely that for these bilinguals a shorter articulation time and a larger memory span in the dominant language were a consequence of a higher level of proficiency in the same languages. If this interpretation is accepted, these findings were unsurprising.

The articulation time measures for the FS bilinguals indicated that the level of bilingual fluency for these individuals was high as performance was equivalent to that of native speakers in each language. According to working memory theory, the shorter articulation time in Finnish than Swedish for these individuals, should have occasioned a larger memory span in Finnish. The FS group, however, showed no difference in word span between the languages: a finding that could not be accounted for in terms of a simple working memory explanation of the relationship between speech rate and memory capacity.

One explanation of the pattern of performance by the FS group was that the equivalence in memory span between the languages was indicative of a corresponding equivalence in the strength of long-term memory representations for Finnish and Swedish. Alternatively, it could be argued that a shorter articulation time for Finnish may have attenuated putative stronger long-term memory representations in Swedish as a consequence of receiving schooling in the same language. These alternatives were tested in Experiment 4 by replacing word items with phonotactically legal Finnish and Swedish non words. This manipulation of lexicality controlled for the putative variation in the strength of long-term representations and allowed the examination of the independent effect of articulation time on memory span.

The findings of Experiment 4, were comparable to those of Experiment 3 in that they indicated that performance on the articulation task by the FS bilinguals was equivalent to that of the FF and SS bilingual types in their respective dominant languages. The results of the memory task showed that FS obtained a larger span in Finnish than Swedish. In this case, performance on the articulation task predicted performance on the memory span task for the three bilingual types. Thus, when the differential in the strength of long-term memory representations was equated across the groups, articulation time was a reliable predictor of bilingual memory performance for all groups. This finding was interpreted as evidence of an interplay between speech rate and long-term memory representations in mediating the bilingual memory capacity.

The above findings would have allowed stronger conclusions to be made had the pattern of performance on the articulation task in of Experiments 4 mirrored that of Experiment 3 more closely. To explain, it will be recalled that one feature of the results of Experiment 3 was that the relationship between the languages varied as a function of bilingual type. For FF and SS the relationship between Finnish and Swedish articulation time was consistent with in the pattern of language dominance, whereas the target FS group performed equivalently to native speaker performance in each language. In Experiment 4, however, performance on the articulation task did not vary in a comparable manner to Experiment 3 as here the SS group also obtained a faster articulation time in Finnish than Swedish. This pattern of results suggested that the non word stimuli were not precisely matched between Finnish and Swedish. Consequently, the performance by FS on the memory span task could be interpreted as simply reflecting a lower degree of difficulty (however defined) for the Finnish non words.

Although a putative lack of equivalence between the non word stimuli constrained the conclusions that could be made with regard to the effect of long-term representations on memory span, some support for the importance of this factor in mediating memory capacity was obtained by comparing the magnitude of the language difference in both the articulation and memory span tasks in Experiment 4. It will be noted that although the SS group had a shorter nonword articulation time in Finnish than Swedish the magnitude of the difference between the languages was 115 msec/word compared to 186 msec/word and 242 msec/word for the FS and FF groups respectively. A comparable pattern of performance was present in the non word memory task where the magnitude of the language difference was as follows: SS = .22, FS = .67, and FF .92. In addition, articulation time in Finnish was reliably longer for the SS group compared to FF and FS. Thus, although the SS group did not obtain a shorter articulation time in their dominant language, the pattern of findings indicated that performance varied as a function of bilingual type with respect to magnitude of the between language relationship.

It was, therefore, concluded that the outcome of the articulation task in Experiment 4 was partly modulated by a lower level difficulty for the Finnish non words. This lack of equivalence between the languages for the non word stimuli, however, did not detract from the finding that non word articulation time predicted the magnitude of between-language relationship in the memory span task more consistently and reliably for the three bilingual types than word articulation time. These findings, thus, suggested that the strength of long-term memory representations was a pervasive mediator of bilingual memory performance.

10.3: Memory Span and Digit Representation

The lack of consistency in the representation of digits across bilingual studies and the consequent difficulty in interpreting these findings has been emphasised sufficiently and is not rehearsed here. Instead, this section focuses on the series of studies that emanated from the observation that between-language performance in speech rate tasks varied depending upon the method used to estimate this variable. A logical progression was to consider the consequence of digit representation on memory span. A study by da Costa Pinto (1991) demonstrated that in the bilingual's dominant language, the representation of digits as numerals or digit words was of no import. When performance was specified in the less-dominant language, however, reading time was slower for numerals than digit words.

An obvious prediction based on working memory theory, therefore, was that in the less-dominant language a shorter reading time for digit word stimuli should occasion a larger memory span for these stimuli in relation to numerals, whereas in the dominant language numeral and digit word span should be equivalent. This prediction was tested in Experiment 6 and resulted in a surprising and, arguably, the most interesting finding arising from the studies presented in this thesis.

10.3.1: The Numeral Advantage Effect

The findings of Experiment 6 indicated that for a group of Spanish-dominant, Spanish-English bilinguals, performance on the reading task was unrelated to performance on the memory span task. Instead, and quite unexpectedly, numeral span was greater than digit word span regardless of language. In Experiment 7, an articulatory suppression secondary task was introduced into the design to test whether the pattern of performance for English present in Experiment 6 was a consequence of the digit sequences being rehearsed subvocally in the non-target language and translated into the target language at the point of recall. Had this been the case, the numeral advantage effect in the less dominant language could be explained in terms of a less-demanding coding process for language-neutral numerals than language-specific digit words. Whilst the possibility may have been responsible for the numeral advantage effect in English (the less dominant language), it certainly did not account for the same pattern of findings in Spanish (the dominant language).

The findings of Experiment 6 indicated that articulatory suppression had no effect on the pattern of findings in the silent recall condition in where, consistent with the results of Experiment 5, a numeral advantage effect was present for both Spanish and English. This finding, thus, discounted the possibility that a larger memory span for numerals in English was mediated by phonological loop functioning and translation-based strategies.

Although a memory span advantage for numerals over stimuli, such as letters and words other than digit words (e.g., Cranell & Parrish, 1957) and variation between different categories of stimuli, such as colours, letters, geometric shapes, etc., (e.g., Miller, 1956), had been reported previously, no prior study had directly compared stimuli that were equivalent both semantically and in terms of articulatory duration. With regard to working memory theory these findings were perplexing as performance on the reading tasks did not predict performance of the memory span task. These findings were, thus, an exception to the otherwise generally robust relationship between word length and memory span and indicated the involvement of factors other than subvocal rehearsal and phonological loop functioning in tasks involving immediate memory.

In terms of furthering understanding of the bilingual digit span effect, however, the finding that articulatory suppression tended toward exerting a differential effect on the language relationship as a function of digit representation, was consistent with the findings of previous studies (da Costa Pinto, 1991; Brown & Hulme, 1992; Chincotta & Hoosain, 1995) and those of Experiment 1. Taken together, the findings of these studies suggested that articulatory suppression abolishes bilingual digit span effects when the stimuli consist of numerals, whereas for digit word representations of number bilingual digit span effects persist (further consideration of the effect of articulatory suppression on bilingual memory span effects was provided in Section 10.5). Furthermore, these findings raised the question as to what factors mediated the superior memory span for numerals in relation to digit words.

10.3.2: The Chunking Hypothesis

One explanation of the numeral advantage effect found in Experiments 6 and 7 was that variation in the 'chunkability' of numerals and digit words arising from, a priori, differences in familiarity between the items occasioned the superior memory span for the former representations of digits. This explanation generated the prediction that if numerals have a greater predisposition toward being chunked than digit words, this would occasion fewer transposition errors for the former in relation to the latter representations. The logic of this prediction was as follows. If the organisation of material into chunks entailed the recoding of discrete items (e.g., 8, 4, 1) into single units of information (e.g., 841), recall attempts for high chunkability items should be more all or nothing than for low chunkability items. Taking the example above, once the individual items 8-4-1 are unitised into the chunk 841 it seemed reasonable to suppose that the chunked unit would be less likely to be recalled as, say, 814. Correspondingly, once individual items are recoded into a chunk, this unitised group would be less prone to substitution errors. Following the same example, this suggests that 841 would be less likely to be recalled as say, 871.

If a putative variation in the relative strength of associative connections for numerals compared to digit words and a consequent variation in the predisposition toward chunkability, occasioned the numeral advantage effect, the chunking hypothesis, thus, predicts specific differences in the error patterns for the distinct digit representations. Moreover, by contrasting the frequency and type of errors made in each language some indication would be provided as to whether differences in the processing of these stimuli were present in bilinguals.

The chunking explanation of the numeral advantage effect was tested in Experiment 8. In addition, the effect of random generation on the relationship in memory span between numerals and digit words was also examined. The earliest formulation of working memory theory (Baddeley & Hitch, 1974) posited that the central executive played a crucial role in the transformation of information into more efficient codes such as chunks. Unfortunately, since then relatively little work has been undertaken to examine the involvement of the least understood component of the tripartite working memory architecture in chunking processes (see, e.g., Baddeley, 1996). Moreover, chunking explanations of information processing have received little attention in recent years owing to the severe restrictions placed on defining chunk size in a manner that avoids circularity (Simon, 1974).

The findings in Experiment 7 indicated that although articulatory suppression induced a general decrement in memory span performance it did not affect the superior recall for numerals relative to digit words. This finding supported the view that the factors responsible for the mediation of the numeral advantage effect were not dependent upon phonological loop functioning and subvocal rehearsal. It was, thus, reasoned that articulatory suppression would not occasion different error patterns for numerals and digit words in either language. On the other hand, given the hypothesised involvement of the central executive in mediating the numeral advantage effect, it was predicted that the random generation task would occasion an increase in order errors relative to the remaining recall conditions.

The findings of Experiment 8 indicated that digit word memory span was greater for Spanish than English. In addition, a numeral advantage effect was present for English across all three recall conditions. No numeral advantage effect, however, was observed for Spanish, and numeral spans were equivalent between the languages. These findings, thus, only partially replicated the findings of Experiments 6 and 7. Nevertheless, inspection of the means indicated that the trends, although not significant, were all in the right direction.

The motivation for this study, however, was to obtain error data with which to test the chunking hypothesis. The errors analysis indicated that a greater proportion of order errors was made for digit words than numerals. The random generation task occasioned a greater proportion of transposition and substitution errors relative to the remaining recall conditions. A difference in the frequency of transposition errors was also present between the articulatory suppression and control recall conditions. This finding suggested that the phonological loop played an important functioning in retaining the serial order of items in readiness for recall.

Taken together, these findings were consistent with the suggestion that the central executive plays an influential role in memory span tasks. It was not possible on the basis of these findings alone to determine whether the effect of random generation on the pattern of errors was specifically due to a disruption of the organisation into chunks, or a consequence of the greater cognitive demands required by this task.

Transposition errors are the most commonly observed errors, particularly at supraspan lengths and are, thus, not necessarily occasioned by the disruption of central executive processes (Henson, Norris, Page, & Baddeley, 1996). In order to test whether the observed increase in the frequency of transposition errors under random generation could be attributed to the putative involvement of the central executive in chunking processes the performance for a set of unfamiliar representation of digits was examined.

The logic of using novel representations of number was as follows. It is generally agreed (e.g., Simon, 1974) that the integration of discrete stimuli into chunks is largely mediated by processes requiring prior knowledge of the items in long-term memory. It was reasoned that novel representations of digits, in the form of playing cards modified from a traditional English deck, would be sufficiently unfamiliar to exclude the likelihood of the availability of long-term representations and, thus, diminish the role of chunking processes.

As predicted, the findings of the playing card memory span task indicated that no difference was present in the frequency of transposition errors across the three recall conditions. Thus, when the level of familiarity with the stimuli was low, random generation did not occasion an increase in an error category reasonably expected to be associated with chunking. Moreover, it will be recalled that for the numeral and digit word stimuli articulatory suppression occasioned a greater frequency of transposition errors relative to the control conditions: a finding taken to suggest the role of subvocal rehearsal in maintaining serial order. The finding that no difference in the frequency of transposition errors was present between recall conditions for the playing cards further supported the view that chunking processes were absent for playing card stimuli relative to the more familiar stimuli as, in this case, the disruption of subvocal rehearsal did not occasion a greater number of transposition errors relative to the control condition.

The random generation task did, however, occasion an increase in the frequency of substitution errors relative to the remaining recall conditions. In particular, the finding that the pattern of substitution errors for the playing cards mirrored that present for the more familiar representations of digits suggested that the increase in substitution errors under random generation for both familiar and unfamiliar material was not related to chunking processes. If this was the case, no differences between the recall conditions should have been present for the unfamiliar material where chunking was not expected to be an important moderator of performance.

One explanation of these findings, therefore, was that random generation made specific demands on the resources required for the transcoding of visual information into storage codes. These cognitive resources were likely to have been independent of processes required for the transcoding of visual stimuli into phonological codes as the random generation task required overt articulation and was, thus, likely to have engaged the articulatory control process within the phonological loop. To explain, the requirement of the memory task necessitated the information to be transcoded into codes capable of storage and retrieval within working memory. Under articulatory suppression, and verbal random generation however, the engagement of the phonological loop prevented the recoding of visual stimuli into phonological codes. It, therefore, seemed reasonable to suggest that under both these secondary tasks the material was likely to be retained in some non phonological code: an obvious alternative being a visual code.

Taken together, the present findings suggested a dual contribution of the central executive in memory span tasks as follows. Firstly, the increase in frequency of transposition errors for the familiar material and the lack of an effect of random generation for the same error category for the unfamiliar material indicated a central executive involvement in the mediation of chunking processes. Secondly, a higher frequency of substitution errors under random generation relative to the remaining recall conditions was present for both familiar and unfamiliar representations suggested a, quite separate, central executive contribution in the transcoding of visual stimuli into, probably, visual codes. In addition, the finding that the magnitude of the increase in substitution errors under random generation relative to the remaining recall conditions was greater for the playing card stimuli than for numerals and digit words was consistent with the notion that the putative involvement of the central executive in the transcoding process was more complex for the unfamiliar than the familiar representations of digits. Taken together, these findings, thus, demonstrated a dissociation of the multi-faceted role of the central executive in memory span tasks (Baddeley, 1996).

Although findings of Experiment 8 were useful in indicating differences in processing between numerals and digit words and contrasted the hypothesised effects of chunking between familiar and unfamiliar representations of number, the failure to replicate the numeral advantage effect observed in Experiments 6 and 7 clearly constrained the conclusions that could be based on this study. In particular, the finding that random generation did not eliminate a superior memory span for numerals than digit words when performance was specified in English demanded a degree of caution before the effect of chunking was overplayed. For, if chunking was mediated by the central executive, why did the numeral advantage persist when this component of working memory was disrupted? Moreover, the absence of a language difference in Experiment 8 suggested that, as far as bilingual memory span effects were concerned, the variation in performance between the dominant and less dominant language was not mediated by factors related to a differential level in the strength of associative connections and chunking processes between Spanish and English.

10.4: The Speed of Perceptual Processing

10.4.1: Item Identification

Evidence from studies of monolingual processing suggested that the speed of identification was an important determinant of memory span performance. Dempster (1981), for example, suggested that the word length effect could be accounted for, quite simply, in terms of a variation in item identification: with faster response latencies for short words than long words. Kail (1992), on the other hand, put forward the view that the speed of perceptual processing makes an independent contribution to articulation rate. It seemed plausible that similar factors impinged upon bilingual memory span performance in a corresponding manner. In Experiment 9, therefore, the role of the speed of perceptual processing and item identification as mediating factors in both the numeral advantage and the bilingual memory span effect was examined. Of specific interest was the reliability of an item identification task in predicting the numeral advantage effect in relation to both the dominant and less dominant languages of the bilingual.

It was important to ensure that performance was undertaken in the target language and that responses were independent of vocalization. To meet these criteria, a cross-modal matching task was designed in which the presentation of an auditory stimulus specified whether processing was conducted in the dominant or less dominant, and responses involved a decision as to whether the items were congruent or incongruent. The specifications of this task, unfortunately, did not allow a direct comparison between Greek and English as the articulatory duration of the first stimulus varied between the languages and may have resulted in a tendency for subjects to delay responses until the termination of the auditory signal (Hitch et al., 1989).

The central question of interest, however, was whether response latency for the item identification task predicted the within-language relationship for numeral and digit word stimuli in the memory span task. It was, thus, reasoned that a comparison of the degree to which item identification response latency, articulation time and reading time were associated to memory span performance would provide some indication as to whether the variation in memory span was mediated by a bias in favour of a faster speed of perceptual processing for numerals relative to digit words.

As expected, response latencies were shorter for numerals than digit words in both Greek and English, whereas performance on the reading task varied as a function of language and digit representation in the manner reported in Experiments 6 - 8. The results of the memory span task indicated a larger numeral span than digit word span for <u>both</u> Greek and English: a main effect that did not interact with the recall condition factor. This pattern of findings, thus, suggested that performance on the memory span task was best predicted by the outcome of the item identification task. This observation was supported by the findings of the correlational analysis of the relationship between the estimates of processing and memory span performance: which revealed a logical and interpretable pattern of results. Namely, articulation time was correlated with silent memory span, reading time was correlated with both silent and suppressed memory span, and item identification was correlated with memory span under random generation. These associations were consistent across both languages with the exception of random generation when performance was specified in the less dominant language.

The most notable finding in this study, then, was that for Greek, response latency in the item identification task was correlated with memory span under a secondary task loading that disrupts central executive functioning. This indicated that the numeral advantage effect was not exclusively mediated by a variation in chunking efficiency between numerals and digit words. Instead, these findings suggested that the effect was partly moderated by a variation in the speed of perceptual processing that, in turn, occasioned a bias in favour of faster recognition for numerals relative to digit words.

The digit word reading time measures predicted the equivalence in digit word memory span between the languages and, correspondingly, numeral reading time predicted a larger numeral span in Greek than English. The reading time measures, however, failed to predict the within-language relationship in memory span for numerals and digit words. Performance on the cross-modal matching task, on the other hand, neatly captured the relationship between numerals and digit words in the memory task. Thus, a measure of cognitive performance that was independent of articulation was the more reliable predictor of the relationship between numeral and digit word span.

The associations between the estimates of cognitive processing and memory span suggested by the correlational analysis followed a lawful pattern, particularly when performance was specified in Greek. Namely, the finding that articulation time was only associated with control digit span suggested that, when the phonological loop was functioning normally, the estimate of speech rate that did not require the recognition of print was related to memory span performance. When phonological loop functioning was disrupted by articulatory suppression and verbal random generation, however, articulation time was no longer associated with memory span. This finding was consistent with the view that when subvocal rehearsal is prevented, recall is mediated by non phonological factors.

The reading time estimate, on the other hand, correlated with memory span under both the silent and suppressed recall conditions. The degree of association between reading time and silent recall was twice the magnitude of that between articulation time and silent recall. This suggested that the additional visual recognition component required in the reading task increased the degree of association between reading time and visual memory span. The finding that reading time was associated with suppressed recall was consistent with the view that visual processes are an important determinant of memory capacity when phonological processing is prevented, and further supported the view that reading time estimates of speech rate are influenced by factors related to visual recognition.

Item identification response latency was associated with memory span under both suppression and random generation secondary loadings to an equivalent degree. The degree of association between suppressed memory span and reading time was significantly greater than for the corresponding relationship with item identification. These findings suggested that when the phonological loop and central executive components of working memory were overloaded, the speed of item identification involving non articulatory processes was an important factor in mediating memory span. A natural explanation of this finding was under circumstances when the phonological loop and the central executive were disabled, the visuo-spatial sketchpad played an important role in storing the visual material: a notion that is examined further in the following section.

As far as the factors that determine bilingual digit span performance, were concerned, the findings of Experiment 9 suggested that when responses did not require articulatory processing, the pattern of performance for Greek and English was broadly comparable in that response latency was faster for numerals than for digit words. This provided some suggestion that the variation in bilingual digit span may, in part, be occasioned by the preparation of output gestures and not exclusively by articulation time per se: although the two factors were naturally likely to be interrelated.

Two potential problems with Experiment 9, however, demanded a degree of constraint before the impact of non articulatory factors in mediating the bilingual digit span effect could be accepted. First, it could not be ascertained whether the language neutral representations of digits were processed in the target language in the item identification task. That is, although the cross-modal matching task was designed to ensure that processing was conducted in the specified language, it was plausible that the language-neutral numeral stimuli may have been processed in the dominant language regardless of the target language. This may have resulted in a simple mapping process whereby the mental representation of the digit elicited by the first auditory stimulus was matched with the second visual stimulus in a manner that did not involve a lexical search for the appropriate item in the target language.

A second, perhaps more fundamental, objection was the confound between the temporal duration of the auditory stimuli in the item identification task and language dominance. Here, the articulation duration of the Greek stimuli was consistently longer than the English equivalents. This made it injudicious to compare performance between the languages given the natural tendency for subjects to postpone their responses until the presentation of the auditory stimulus terminated (Hitch et al., 1989). Therefore, although performance on the item identification task between Greek and English was similar, it was impossible to gauge whether this equivalence was an indication of broadly equivalent, non articulatory, mediating factors or whether the shorter durations for the English auditory stimuli accelerated responses in this language. Under these circumstances, the conclusions that could be drawn from the findings in terms of the factors that determined the bilingual digit span effect were severely curtailed.

One potential solution with regard to eliminating the difference in the articulatory duration of the auditory stimuli was to artificially shorten the word length of the Greek items (or conversely extend the length of the English ones). It was considered that such measures, however, would reduce the validity of the findings. Alternatively, by reversing the modal order of the stimuli (i.e., visual first- auditory second) it may have been possible to limit the effects of different word lengths for Greek and English. Under these circumstances, however, control over the language specificity in the processing of language-neutral stimuli would have lost and the subjects were likely to process numerals in the more dominant language regardless of the language being tested. Neither of these two solutions was considered satisfactory, thus, the strength of the conclusions in terms of the factors that mediate the bilingual digit span effect was severely limited.

10.4.2: Visuo-Spatial Short-Term Memory

The numeral advantage effect has, thus far, been discussed under the general rubric of processes broadly related to chunking. The findings of Experiment 9, however, indicated that the variation in the speed with which numerals and digit words were perceptually processed was an influential factor in determining the numeral superiority effect, particularly when central executive functioning was disrupted. At this juncture, therefore, an alternative interpretation of the factors that mediated the superior numeral span was considered.

So far, it has been proposed that a variation in the strength of associative connections between numeral and digit word stimuli provides a plausible, account of the factors that mediate the numeral advantage effect. The pattern of errors found in Experiment 8 was interpreted within this general framework and was taken as support for the notion that the effect was modulated by factors related to chunking. The findings of Experiment 9, on the other hand, suggested that item identification and the speed of visual perceptual processes were independently associated with memory span performance under a secondary task loading that disrupted central executive functioning, and hence the recoding of information in chunks. These results provided a strong suggestion that the numeral advantage effect was partly mediated by visual recognition and visual storage processes.

Recent theoretical developments (Logie, 1995 for a review) suggested that the visuo-spatial scratch pad component of working memory is structurally and functionally analogous to that of phonological loop. Although there are clear similarities between these two working memory slave systems, dissociations of visual and spatial processing (e.g., Quinn & McConnell, 1994; Logie, 1986, 1989) indicated that the visuo-spatial scratch pad architecture is somewhat more complex than that of the phonological loop.

In a modified model of the visuo-spatial sketch pad, Logie (1995) proposed that this component of working memory consists of temporary visual and spatial stores into which visual and spatial information respectively enters via long-term memory representations of the material being processed. Entry into either the passive visual or the dynamic spatial storage system is dependent upon the nature of the information that is activated. The traces in the visual store are subject to both decay and interference from new information but can be refreshed by the action of the spatial store. In addition to providing a rehearsal-like renewal or regeneration of fading activations, the spatial store extracts information for the planning and execution of movement.

This is not the place to discuss Logie's (1995) reconceptualisation of visuo-spatial short-term memory in any great detail except to state that this modified model of the visual component of working memory allows a modest degree of theoretically motivated speculation with regard to the role of the visuo-spatial sketch pad in determining the numeral advantage effect. It is reasonable to argue, for example, that memory span for numerals is advantageous on two counts. First, numeral representations of digits comprise single characters, whereas digit words are multi-character in nature (e.g., 1 vs. o-n-e). This difference in visual 'area' between the stimuli could, arguably, result in a corresponding variation in the demands made on the limited capacity of the visual store. Under these circumstances, single character units would be stored more efficiently than multi-character units: a of visual area effect possibly analogous to the word length effect for phonological material.

Second, if it is accepted that representations of digits occur more often as numerals than digit words, it is plausible that this variation in frequency occasions a corresponding variation in the strength of long-term memory representations. According to Logie's (1995) model, entry into the storage spaces within visuo-spatial short-term memory is gained only via long-term memory. It seemed plausible, therefore, that the putative stronger long-term memory representations for numerals relative to digit words occasion a more efficient regeneration of fading activations in the visual store: a process akin to the redintegration of decaying traces within the phonological loop (e.g., Hulme, et al., in press).

An explanation of the numeral advantage effect in terms of visuo-spatial short-term memory, thus, accounted for the findings of Experiments 9, wherein a random generation secondary task loading did not eliminate the numeral advantage effect. For, although Logie's (1995) revised model posits that long-term memory representations play an important role in mediating the transfer of perceptual information to visual memory storage, in this case the central executive acts as a conduit between long-term and short-term stores rather a transformer and organiser of information into more efficient codes as originally envisaged by Baddeley and Hitch (1974).

Correspondingly, if the view that the numeral advantage effect is mediated by the visual component of working memory is correct, secondary tasks designed to disrupt the visual storage system should eliminate the superior recall for numerals. Seminal evidence in support of this notion was found by Chincotta, Baddeley, Jarrold, Underwood, Wresinski, Abd Ghani, and Adlam (1997) in which a visuo-spatial suppression task (spatial tapping) eliminated the superior numeral span relative to digit words. Further studies that examine the involvement of a limited capacity short-term visual store in mediating the numeral advantage effect by using visual masking and random generation techniques are currently in progress.

The above discussion, then, suggests that numeral advantage effect could, quite plausibly, be mediated by the functioning of the visuo-spatial sketchpad component of working memory that, in turn, is modulated by parameters closely resembling those known to be influential determinants of phonological loop functioning. It should be noted, however, that this account of a putative visuo-spatial memory involvement in mediating the numeral advantage effect was not wholly incompatible with the chunking explanation of the phenomenon. That is, it seemed possible that the hypothesised variation in the strength of associative connections between numerals and digit words operated in manner that mimics the predicted effects of chunking in tasks of immediate memory. In this case, however, the convenient shorthand of the term 'chunking' would be stipulated as the process whereby putative variation in coding efficiency is modulated by the limited storage capacity of the visual memory store.

10.5: The Role of Speech Production in Memory Recall

10.5.1: The Planning of Articulatory Gestures

Notwithstanding the limitations of Experiment 9, these findings were consistent with the notion that the variation in memory capacity between the dominant and less dominant languages was, in part, occasioned by a difference in the preparation of articulatory gestures prior to output appeared plausible. In fact, there is seminal evidence that the planning of articulatory gestures is an important factor in mediating both speech rate and memory span: although this is an area of research that has not received much attention of late. Chase, Lyon, and Ericsson (1979), for example, have shown that the degree of association between speech rate and memory span was dependent upon the number of items used to estimate the rate of subvocal rehearsal. That is, when the rehearsal sequence consisted of subspan lengths (e.g., 3 or 4 digits), no relationship was obtained between articulation time and memory span. For rehearsal sequences of supraspan length (e.g., 6 digits) the correlation between the variables increased to about .50.

Chase et al. (1979) compared the relationship between several components of the speech output process and memory span in greater detail. Recall execution time (the average inter-item interval during output), for example, correlated with memory span (- 0.38). More important, a measure that quantified the time taken between the onset of the instruction to start recall and the output of the first item (rehearsal start time) correlated to higher degree with digit span (- 0.59): although no indication of whether these correlations were reliably different was provided. Chase et al. (1979) concluded that the correlation between memory span and output time was largely artifactual as individuals with low memory spans were likely to be slower in recalling the material.

More recently, Cowan, (1992) examined the relationship between a variety of speech output timing measures and memory span. Cowan (1992) found that response time (the total time taken to recall the memory sequence from the offset of the presentation sequence to the end of the recall sequence), pronunciation time (duration of the response minus the preparation time and, and speech time (pronunciation time minus the pauses) were correlated with memory span (0.59, 0.60, & 0.82 respectively). In this case, however, preparation time (the temporal delay from the offset of the presentation sequence to the onset of the response sequence) was not correlated with memory span. Thus, the measure that corresponded most closely to the Chase et al. (1979) index of recall start time was not associated with memory span.

One explanation of the lack of convergence between the Cowan (1992) and Chase et al. (1979) studies was that the measures were not strictly comparable. That is, Cowan (1992) tested subjects aged between 4 and 5 years. Children of this age are generally considered to be at a stage where the use subvocal rehearsal as a strategy for improving recall is not widely used (Gathercole & Hitch, 1993). This may have been a crucial factor in the failure to replicate the findings of Chase et al. (1979). On this count, then, it was argued that the findings of Cowan (1992) did not refute the suggestion that the planning of articulatory gestures is unimportant in mediating memory span. Further evidence in support of the view that temporal pauses during output are not a reliable predictor of memory span performance was found in a cross-linguistic study of Chinese and English speaking schoolchildren by Stigler, Lee, & Stevenson (1986). Although the Chinese speakers obtained larger digit spans that the English speakers, no difference between the groups was present in terms of output response time.

It seemed logical to suppose that the intervals in output sequences are likely to heavily influenced by factors related to the cognitive effort required for recall. Under these circumstances, the quantifying of relatively noise-free estimates of the timing of articulatory gestures must be near to impossible. Thus, it was reasonable to suggest that qualitative differences are likely to be present between the measures. This could explain the lack of a clear association between timing intervals generated by the rapid repetition of items during covert speech tasks and similar intervals during the output of recall sequences. In order to come to worthwhile conclusions as to the factors that inherently determine the timing of speech rate, therefore, it makes more sense to examine pauses and intervals during overt articulation tasks rather than during recall output.

Such an approach was taken by Hulme et al. (1984) in an examination of the relationship between speech rate and the development of short-term memory span. These authors addressed the question as to why memory span increase with age and posited two theoretical possibilities. Firstly, one view would hold that children's development is accompanied by a faster rate of articulation of individual words. An alternative position is that the articulation of words remains constant but that speech becomes more continuous, thereby resulting in shorter time intervals between words. Either of these two explanations, therefore, could account for the increase in speech rate as a function of age: although the possibility that both factors operate in tandem was not discounted.

Hulme et al. (1984) compared the time taken to articulate individual words with the time taken to articulate a word triad consisting of the same items. This analysis revealed that the articulation time for individual items was shorter as a function of age and suggested that faster articulation was one important factor in mediating the development increase in speech rate. Unsurprisingly, an equivalent pattern was obtained from the analysis of word triplets. The crucial question however, was whether the increase in triplet articulation rate was a consequence of shorter individual articulation time or whether there was a corresponding reduction in the intervals between the words that comprised the triplet. Thus, the mean total interval between words was calculated by subtracting the individual articulation time for each word from that of the triad sequence.

The analysis of mean interval time revealed a complex pattern of results. Namely, the shortest intervals were found for words of medium word length, then long word length, and finally short word length: these results were consistent across both the 8 and 10 year old groups. More important, the analysis of intervals contrary to the analysis of individual word and triplet word length articulations, did not indicate a difference between the age groups. On the basis of these findings, then, Hulme et al. (1984) concluded that the developmental increase in speech rate may be fully accounted for in terms of a corresponding increase in the speed at which individual words can be articulated.

One problem with the Hulme et al. (1984) study was that the manner by which the time intervals between the items were calculated resulted in measures of the inter word pauses within the three word articulation phrase. This index of pauses between words, thus, ignored what is termed as the intra triplet interval (the duration between the end of one articulated triplet and the commencement of a subsequent). There is some evidence that inter word and intra sequence pauses are qualitatively different. For example, in a recent, detailed examination of the relationship between the temporal intervals in a speeded word pair articulation task and memory span, Hewes, Jarrold, and Baddeley (1997) compared the degree of association between inter pair (the interval between the first and second word pair) and intra pair (the pause between the second and first items in the word pair) intervals and memory span. This analysis revealed a remarkable and consistent pattern of reliable correlations between intra pair intervals and memory span. On the other hand, the inter pair intervals were not correlated with memory span performance.

Geffen and Luszcz (1983) had also examined the variation in inter word pauses although not in relation to memory span. These authors noted that low frequency words took longer to read aloud high frequency words. Moreover, the increase in reading time was related to a corresponding increase in the interval between items. Although, the precise nature of the pauses remained unspecified, these findings led Geffen and Luszcz (1983) to claim that the variation in inter word intervals as a function of word frequency cast doubt on the explanation of the word length effect in purely in terms of articulation.

Taken together the outcome of studies that examined measures of the timing of spoken recall in some detail did not provide convincing support for the view that output measures are a critical determinant of short-term memory capacity (the interpretation of output delay is considered more fully in Section 10.5.2). Instead, a plausible explanation of the relationship between speech rate and memory span lies in time taken to prepare the articulatory gestures necessary for the vocalisation of items. It seemed, however, that the intra pair articulation interval is associated with memory span, whereas the inter pair interval is not. This qualitative distinction between intervals is a potentially exciting one that could yet provide an alternative account of the relationship between speech rate and memory span. Although, any firm conclusions concerning the precise nature of the association are pending further research.

In terms of the bilingual memory span effect, however, it was reasonable to speculate that the neural programs required for the activation of speech codes for items in less familiar languages will be relatively slower than for the dominant language. This, as yet, unexplored factor may prove to be a highly influential determinant of the variation in bilingual short-term memory capacity.

10.5.2: Output Delay

Although the effect of articulatory suppression in abolishing the word length effect is a generally robust finding in the working memory literature (Baddeley, et al., 1975), recent developments have suggested that the relationship between speech rate and memory span is less straightforward that has previously been considered (e.g., Caplan & Waters, 1994; Service, 1996). Cowan et al., (1992) suggested that the effect of word length may be accounted for by differences in overt speech time during output rather than variation in the rate of subvocal rehearsal rate.

Although Cowan et al., (1992) provided what appeared to be convincing evidence in support of the view that output delay hypothesis, it did not address the criticism that a simple version of the effects of output on memory performance failed to account for the finding that articulatory suppression eliminates the word length effect (Baddeley, et al., 1975). For, if the differential memory span for long and short words is modulated by temporal factors during the recall of the items, word length effects should still be present. Avons et al., (1994) put forward the more moderate view that word length effects could be accommodated by working memory theory if the temporal capacity of the phonological loop was not regarded as the sole factor in mediating memory span performance.

At first blush, the arguments presented in the preceding with regard to the relationship between bilingual speech rate and memory span provided little support for the view that output delay was an influential factor in mediating the bilingual memory span effect. The main evidence in favour of this notion lay in the findings of Experiments 2 and 5 that demonstrated that articulation time (arguably the most appropriate index of output time) was unrelated to memory span performance. One explanation could be that these studies presented digit stimuli, therefore, a confound between the variation in digit name word length and language could not be avoided. Given the relatively large variation in syllable length between Finnish and Swedish, it was, thus, unsurprising that Finnish-dominant bilinguals articulated the items faster in the less dominant language (Experiments 2 & 5). Under these circumstances, therefore, it was reasoned that articulation time could not be considered an accurate estimate of output delay as the difference in spoken duration between the languages was artificially exaggerated.

In Experiment 3, however, when word stimuli were equated for syllable length the pattern of findings indicated that articulation time varied as a function of bilingual type. That is, for the FF and SS bilingual types articulation time for one and three syllable words was shorter in their respective dominant languages. This finding suggested that when the items were comparable in terms of syllable length, articulation time was consistently longer in the less dominant language. Under these circumstances, therefore, it seemed plausible that a variation in output delay between the languages could be an influential mediator of the bilingual memory span effect. This hypothesis was tested in Experiments 10 and 11 and the Cowan et al., (1992) paradigm was adapted to examine the moderating effect of output delay in immediate memory performance in bilinguals. The findings of these studies were to provide some interesting evidence with regard to the lack of power of articulation time in predicting the outcome of bilingual digit span performance.

As expected, then, the findings of Experiment 10 indicated that Spanish-dominant, Spanish-English bilinguals articulated two and three syllable high frequency words faster in their dominant language and that, correspondingly, a faster speech rate in Spanish was associated with a larger memory span in the same language relative to English. The manipulation of word length in the first-and second-half of the presentation sequence, however, was inconsequential in determining the overall proportion of correct responses in either language. The results of Experiment 10, thus, suggested that the word length of the second half of the recall sequence was critical in determining memory performance for both directions of recall. These findings, therefore, were consistent with the view that memory span capacity was modulated by the temporal capacity of the phonological loop and, thus, did not support the output delay hypothesis. Moreover, it could reasonably be deduced that the variation in memory span between Spanish and English was a direct consequence of a corresponding variation in articulation time between the languages that occasioned a slower rate of subvocal rehearsal when performance was specified in English relative to Spanish.

The next study, examined whether the divergence between the findings of Experiment 10 and those of Cowan et al., (1992), was a consequence of a difference in the frequency of items. The findings of Experiment 11 indicated that the word length of the initially presented items was critical in determining memory span although, this pattern of results applied only for the forward direction of recall when performance was specified in Spanish. Thus, when the frequency of the items approximated that of the words used by Cowan et al., (1992), partial support was obtained for the view that output delay was an influential moderator of memory span.

Taken together, the findings of Experiments 10 and 11 moderated the Cowan et al., (1992) output delay hypothesis and suggested that the effect of word length on recall occurred as a function of item frequency. That is, when the frequency of the items was high, temporal capacity was an influential modulator of recall performance. Correspondingly, when word frequency was low, recall was mediated by the rate of trace decay from the phonological store. These findings were consistent with the view that short-term memory is supported by the process of redintegration that assists the pattern completion of decaying traces held in phonological storage (Hulme et al., 1995; Brown & Hulme, 1995).

10.5.3: Redintegration Efficiency and Subvocal Rehearsal

The difference in processing between high and low frequency items discussed above provided some indication as to why the pattern of findings of the experiments presented in this thesis were inconsistent with the notion that the bilingual memory span effect was principally mediated by the rate of subvocal rehearsal. If it is accepted that the frequency of digit stimuli is relatively high in both the dominant and less dominant languages of the bilingual, this could explain why the variation in articulation time between languages was not the most crucial determining factor in bilingual memory span performance. Instead, based on the findings of Experiments 10 an 11, it seemed plausible that the bilingual memory span effect was modulated by factors related to strength of long-term memory representations and a variation in the efficiency of the redintegrative process.

To explain, the evidence presented in this thesis suggested that memory performance is modulated by the rate of subvocal rehearsal that refreshes decaying traces through a redintegrative process. Thus, when performance is specified in the dominant language of the bilingual, it is reasonable to argue that memory performance is bolstered by relatively strong long-term memory representations and a faster rate of subvocal rehearsal. Correspondingly, when performance is specified in the less dominant language, the long-term representations are relatively weaker and the rate of subvocal rehearsal is slower. Under these circumstances, memory span will be greater in the dominant than the less dominant language, and hence the bilingual memory span effect.

There is clear evidence, however, relationship between the languages of the bilingual is not always so orderly. The findings of Experiment 5, for example, indicated that there are circumstances in which bilinguals articulate digits faster in the less dominant language. Under such conditions, however, the findings of Experiments 2 and 5 and Elliot (1992) indicated that a shorter articulation time in the less dominant language was not sufficient to occasion a corresponding larger memory span in the language. There is some evidence, however, that when speech rate is faster in the less dominant language bilingual memory span occasions an equivalence in memory performance between the languages (see also Experiment 4) rather a correspondingly greater span in the language in which speech rate is fastest. In other words, factors related to speech rate alone are not sufficient to overcome the role of long-term memory representations in mediating bilingual memory capacity.

So, how may the explanation that proposes a dual contribution of factors related to strength of long-term memory representations and a variation in the efficiency of the redintegrative process account for the pattern of findings under these circumstances?

It was logical to suggest that under the conditions just outlined, a shorter articulation time in the less dominant language quite plausibly gave rise to a faster rate of subvocal rehearsal when performance relative to the dominant language. It was also natural to assume that the strength of long-term memory representations would be weaker in the bilingual's less dominant language despite a putative advantage in terms of rehearsal rate. The efficacy with which the redintegrative process was capable of engaging in the pattern completion of the decaying traces in phonological storage was, therefore, likely to be a highly influential factor in determining the outcome of memory performance. This dynamic interplay between rehearsal rate and redintegrative efficiency seemed a plausible mechanism by which the variation in bilingual memory span effects was modulated and which, by extension, occasioned the attenuation of a natural bias in favour of a larger digit span in the dominant language.

The further work that was clearly required to specify the precise parameters that determined the circumstances under which the attenuating effect resulted in an equivalence in bilingual memory span performance lay beyond the scope of the present thesis. To achieve this objective, greater attention needed to paid to the relationship between magnitude of the difference in subvocal rehearsal between the languages and the corresponding magnitude of the difference in the strength of long-term memory representation.

10.6: Articulatory Suppression

It would be remiss to omit a consideration of the effect of articulatory suppression on bilingual digit span in this final chapter. The deliberation of this issue was purposely postponed until other aspects of this thesis were discussed and clarified and in order to allow a more comprehensive analysis of the effect of this secondary task loading on memory performance. There is no need to reiterate that the articulatory suppression procedure is not without its critics (Parkin, 1988, 1993). Levy (1981) and Margolin, Griebel and Wolford (1982), for example, have argued that the additional processing load demanded by concurrent articulation impairs recall ability through increased demands made on attention. In addition, there is some evidence that the effect of articulatory suppression on long-term memory diminishes with extended practice (Baddeley, Lewis, Eldridge & Thomson, 1984). Notwithstanding these criticisms, the effects of articulatory suppression in eliminating word length effects and preventing phonological coding are highly consistent (Baddeley, Lewis, & Vallar, 1984; Vallar & Baddeley, 1984).

10.6.1: Interpreting the Effect of Articulatory Suppression

It has been argued consistently in the preceding sections that the conclusion by Ellis and Hennelly (1980) that articulatory suppression eliminated a bilingual digit span effect in Welsh-English bilinguals was irredeemably flawed on several counts: the most critical being the lack of a control measure of digit word span and the peculiar combination of presentation modalities. This same objection can be made of the da Costa Pinto (1991) study. In addition, Brown and Hulme's (1992) subjects could hardly be considered bilingual as this sample consisted of schoolchildren in the early years of learning French and as second language. In addition, further complications with this study arise from prolonged articulatory suppression during the recall phase and the use of written numeral responses despite the use of digit words in the presentation sequence (Brown, 1997).

There are reasonable grounds, thus, upon which to disregard the findings of the above-cited studies when evaluating the effect of articulatory suppression on bilingual digit span. Nevertheless, even if the findings of the above-cited studies are discounted, a discrepancy still remained with regard to the effect of articulatory suppression between the findings of Chincotta and Hoosain (1995) and Experiment 1, in which articulatory suppression removed language differences, and Experiments 7, 8, and 9, in which language differences persisted.

The most obvious explanation for this lack of convergence is that the level of bilingual fluency of the subjects varied dramatically between the studies. That is, it was possible that the variation in the effect of articulatory suppression was contingent upon the level of relative bilingual fluency of the subjects. For example, it was plausible that when the level of relative fluency between the languages was low, as in the case of the Brown and Hulme (1992) study, discrete levels of familiarity between the dominant and less dominant languages prevented the effectiveness of articulatory suppression in eliminating the bilingual digit span effect. Under this circumstance, then, the bias in favour of stronger long-term memory representations in the dominant language would result in the persistence of a bilingual digit span effect: as Brown and Hulme (1992) observed. The variation in the effect of articulatory suppression on bilingual digit span could, therefore, be a consequence of different degrees of bilingual fluency where the higher the level of balanced bilingualism, the more likely that articulatory suppression would eliminate the differential digit span between the languages.

This line of reasoning, however, begged the question as to what circumstances are both necessary and sufficient for concurrent articulation to abolish the digit span differentials between the bilingual's language. To illustrate this point, it was necessary to indulge in a degree of theoretical speculation as follows. If it were possible, for example, to test a perfectly balanced bilingual (essentially an individual with native speaker fluency in both languages), a bilingual digit span difference under silent recall conditions could be reasonably attributed to the effect of cross linguistic variation in the articulatory duration of digit names (e.g., Naveh-Benjamin & Ayres, 1986). Furthermore, the elimination of this difference under articulatory suppression, could equally reasonably be attributed to the disruption of subvocal rehearsal (Chincotta & Underwood, 1997). In such a hypothetical scenario, however, these factors are necessary for an equivalence of suppressed memory performance between the two languages, but are not, in themselves, sufficient to guarantee such an outcome. The elimination of a bilingual digit span effect under articulatory suppression should only be theoretically possible if a corresponding equivalence in the strength of long-term memory representations in both languages is also present (Hulme et al., 1991): a not inconceivable possibility given the putative notion of the perfectly balanced bilingual.

This point may be illustrated by reference to the findings of Experiment 1. It will be recalled that numeral reading time did not vary across these bilingual types when performance was specified in Finnish, whereas a difference was present when performance was specified in Swedish. For the SS bilingual type, therefore, numeral reading time in the less dominant language (Finnish) was equivalent to FF performance the dominant language. It has been argued elsewhere in this chapter (e.g., 10.1.2) that numeral reading time is an index of fluency rather than an appropriate estimate of speech rate. It was, thus, reasonable to interpret numeral reading performance by SS in Experiment 1 as some indication that this bilingual type was close to a highly balanced level of bilingual fluency. If this view was accepted, and given the ongoing discussion with regard to the effects of articulatory suppression on bilingual digit span, it would be reasonable to expect that concurrent articulation was more likely to eliminate the bilingual digit span effect for a balanced bilingual type than for a bilingual type with an asymmetric level of fluency between the languages.

The findings of Experiment 1 indicated that articulatory suppression eliminated the bilingual digit span effect for both the SS and FS bilingual types (Figure 2.4). Inspection of the means, however, indicated that the for FF the difference between Finnish and Swedish suppressed memory span although not reliable was 0.43 units, whereas for SS suppressed memory span was identical (4.94) in both languages. This pattern of results was, therefore, broadly consistent with the explanation that the degree of relative fluency and the strength of long-term memory representations between the languages are important modulating factors in determining the equivalence in performance under articulatory suppression (cf. 10.6.3).

It was, thus, reasoned that any explanation that attributed the elimination of bilingual digit span effects under articulatory suppression to a perfect balance in the factors outlined above (i.e., the strength of long-term memory representations and probably an equivalence in the time taken to prepare neural codes for articulation) once the differences in the articulatory duration of digit names and subvocal rehearsal were no longer influential variables was implausible. This, admittedly speculative, description of the conditions necessary for the elimination of bilingual digit span differences under articulatory suppression served to illustrate the sheer improbability of obtaining such an outcome based on these factors alone.

10.6.2: Procedural Variation Across Studies

So, what alternative factors could have been responsible for the elimination of the bilingual digit span effect in some studies and not others? It was reasoned that a more plausible account of the divergent findings with regard to the elimination of bilingual digit span effects was that procedural and methodological differences between studies were likely to have been a major factor in determining the variation in outcome.

A detailed examination of the studies considered valid with regard to evaluating the effect of articulatory suppression on bilingual digit span revealed two important differences between those experiments in which a language difference was abolished under concurrent articulation and those were these differences persisted as follows. The first source of variation between the studies was a difference in the duration of the post-presentation recall interval. The second lay with a procedural difference with regard to the monitoring of the rate of articulatory suppression: these points are now discussed separately.

With regard to the difference in response delay, Chincotta and Hoosain (1995) study and Experiment 1 imposed a 4-second delay between the presentation of the last item and commencement of verbal for both the silent and suppressed recall conditions. On the other hand, the studies in which bilingual digit span effects persisted only imposed a 2-second post presentation delay.

Longoni Richardson and Aiello (1993) and Richardson, Longoni, and Di Masi (1996) found that the effect of phonological similarity persisted when subjects engaged in articulatory suppression for 10 and 20 seconds interval prior to recall. These authors, thus, concluded that memory traces in the phonological store persist for longer durations than is generally assumed (e.g., Baddeley, 1990) and that there is a general reduction in the magnitude of the effect as a function of time. These findings, then, provided a theoretical basis upon which to tentatively suppose that a delay of 4 seconds interpolated with articulatory suppression might occasion a different outcome to that of a 2 second delay with regard to the elimination or otherwise of bilingual digit span effects. That is, the longer the period during which articulatory suppression is maintained, the greater the likelihood that the traces in the phonological store decay irretrievably, and hence the difference in outcome between the studies currently being discussed.

It seemed plausible, that a difference in the duration of post presentation articulatory suppression may have been an important factor in determining the variation in outcome across studies. It remained unclear, however, whether a difference of 2 seconds in the length of post-presentation articulatory suppression between the studies that eliminated bilingual digit span effects and those that did not was the only factor responsible for the variation in outcome with regard to the hypothesised effects of this secondary task on bilingual memory performance.

The notion that the variation in the effect of articulatory suppression on bilingual digit span performance could be accounted for simply in terms of differences in the duration of the post presentation recall interval was weakened by the findings of Experiment 7. It will be recalled that here the interpolation of a 2 second post presentation delay with articulatory suppression eliminated the bilingual digit span effect for numeral stimuli but not digit word stimuli. Of course, the suggestion of differential effects of articulatory suppression on these discrete representations of digits emerged under detailed examination of a non significant interaction and, therefore, cannot be overplayed. Notwithstanding this technical point, however, these findings provided some indication that extending articulatory suppression for 4 seconds after presentation, although of possible importance, was not a crucial factor in determining whether the bilingual numeral span effect was erased or otherwise.

The second, arguably more critical, source of variation between the studies with differential outcomes was that the rate at which the suppression phrase was uttered. In the Chincotta and Hoosain (1995), and Experiment 1 studies, the rate of articulatory suppression was not objectively monitored. Although attempts were made in these two studies to ensure that the pace of articulatory suppression was constant, this consisted of reminding the subjects to modify the rate of suppression whenever the Experimenter perceived a departure from an approximate target of three or four utterances per second. It was reasonable to argue that the lack of precise monitoring of the rate of suppression may have been an influential factor in determining whether the outcome of this (and indeed all) secondary task(s) had the expected effects on performance. One obvious consequence of a failure to control for the pace of articulatory suppression was that subjects may have decreased the rate of articulation as processing demands increased correspondingly resulting in a demand-performance trade-off whereby additional processing may have been undertaken during the increased intervals between utterances (see, e.g., Cowan et al., 1992). This absence of precise monitoring was also a feature of Experiment 7 and may have contributed to the pattern of findings that required a theoretically more complex explanation of the putative differential effects of suppression as a function of digit representation.

By contrast, in Experiments 8 and 9 the rate of articulatory suppression was monitored with the use of a metronome. Under this procedure the subject was, thus, allowed to self-monitor performance in an effective manner and the Experimenter was allowed a greater degree of confidence with which to detect variation in the rate of secondary task performance: although it was accepted that the more subtle deviations would remain undiscovered. Therefore, although the use of a metronome to pace the rate of secondary task performance cannot in itself ensure an absolute and invariable constant rate of articulation, it may be reasonably argued that this procedure goes some way toward meeting the requirement that the speed at which dual tasks are performed remained relatively constant.

It was of some interest, therefore, that under circumstances in which then rate of concurrent articulation was monitored in the above-described manner, the bilingual digit span effect present in Experiments 8 (for digit words) and 9 (for both numerals and digit words) under a silent recall condition, persisted under articulatory suppression. These studies were the only two examples in the bilingual digit span literature in which the pace of suppression was monitored and the delay between presentation of the sequence and commencement of recall was interpolated with articulation for a two-second period.

10.6.3: Erasing the Bilingual Digit Span Effect

Finally, it was worth highlighting the one exception in which paced articulatory suppression erased a bilingual digit span effect. This was found when a variation in strength of long-term memory representations for the stimuli between the languages was controlled (Experiment 8). It cannot be coincidental that the only occasion when prolonging articulatory suppression during a 2 second delay prior to recall resulted in the elimination of bilingual memory span effects was when playing card representations of digits were used. The theoretical consequences of articulatory suppression in eliminating word length discussed above were, thus, present only when the strength of long-term representations for digits was equivalent between the languages when subvocal rehearsal was prevented. This finding was consistent with the theoretical consideration of the effect of articulatory suppression discussed in 10.6.1.

The discussion in this final section, then, has argued that the findings of previous studies in which bilingual digit span effects were eliminated by articulatory suppression were likely to be an artifact of both a protracted period of post-presentation articulation and a failure to adequately control for variation in the rate at which the suppression phrase was uttered. Under these circumstances, it was concluded that the elimination of the bilingual digit span effect under articulatory suppression claimed by Ellis and Hennelly (1980), and Chincotta and Hoosain (1995) has yet to be demonstrated incontrovertibly.

Chapter 11
Summary

The principal aim of this thesis was to re-examine the view that the bilingual digit span effect in Welsh-English bilinguals is mediated by a variation in word-length between the languages (Ellis & Hennelly, 1980). This was conducted in the light of recent theoretical developments in working memory theory, the most significant of which was the realisation that long-term memory representations, particularly phonological ones, are crucially important factors in bolstering immediate memory capacity. This reconceptualisation of the parameters that mediate working memory functioning, however, does not account for findings which demonstrate that bilingual digit span effects are eliminated under articulatory suppression (Ellis & Hennelly, 1980; Chincotta & Hoosain, 1995). For, if the strength of long-term memory representations is indeed a crucial determinant of memory span, it seems inconceivable that articulatory suppression should occasion an equivalence between the dominant and less dominant languages of bilinguals given the likelihood of dramatic variation in the strength of memory representations between the languages.

The bulk of evidence presented here questioned whether Ellis and Hennelly's (1980) conclusion was sustainable from several perspectives ranging from the methodological to the theoretical. The most critical finding, however, was the demonstration that the use of numeral reading as a means of estimating differences in word length, a central tenet of Ellis & Hennelly's (1980) argument, was fundamentally flawed. In the light of this incorrect assumption, additional objections to a simple word length account of the bilingual digit span effect, such as the failure to obtain control measures of digit word span, the use of different samples, mixed modality, and the inconsistent use of number representation become academic.

Although this thesis presented ample evidence to challenge the view that the bilingual digit span effect is mediated exclusively by a variation in word length, it has been noted that Welsh-English bilinguals display a preference for English number names when speaking in Welsh (Ellis & Hennelly, 1980, p.49). Although this fact alone does not undermine the conclusions arrived at here, it may be worth establishing whether predictions generated by the present findings can account for the outcome of a replication of Ellis and Hennelly (1980) in which the classification of bilingualism, estimates of speech rate, measures of digit span are controlled more stringently. Such a study is currently being undertaken and would be a means of dismissing conclusively the view that the bilingual digit span effect is a word length effect (Chincotta & Adlam, in preparation).

It is one thing, however, to highlight the problems associated with a simple working memory account of the bilingual digit span effect in terms of word length and the rate of subvocal rehearsal, and quite another to propose an alternative account of the factors that mediate the variation in bilingual memory span. Although a precise specification of the parameters that modulate bilingual memory span lay beyond the scope of the work presented here, some headway was made in demonstrating the influence of factors such as output delay and long-term memory representations.

Future research involving the systematic manipulation of phonological and semantic long-term memory factors and which examines the effect of these variables on bilingual short-term memory seems a logical way forward. Such an approach has the potential to shed light on both the nature of the redintegrative process and the relative contribution of these factors in mediating the relationship between the bilingual's languages which, in turn, could be informative with regard to understanding the relationship between the organisation of the bilingual lexicon and memory span. Moreover, the use of more informative quantifications of bilingual word frequency, such as subjective frequency (e.g., Murray, 1986), rather than conventional word frequency counts is a basis upon which to further refine the design of future studies.

Progress in specifying the effects of phonological and phonotactic factors on short-term memory capacity (Gathercole & Baddeley, 1989; Service, 1996) suggests that cross-linguistic comparisons will continue to be a productive and informative area of research. Caplan, Rochon, and Waters (1992) and Service (1996), for example, have argued that the phonological complexity of items, such as consonant clusters and extended vowel sounds, are more crucial determinants of memory span than word length. If this view is correct, it suggests that such factors could be an important additional source of variation in mediating cross linguistic differences in digit span (e.g., Chincotta & Underwood, 1997). An examination of the influence of phonological and phonotactic complexity across language families would, thus, be of some interest.

Future examinations of the relationship between word length and memory span, however, should pay close attention to the quantification of word length and what various methods of speech rate estimation actually index. The findings presented here were consistent with the view that bilingual speech rate estimates are likely to be influenced by a range of factors other than articulation time. Given this possibility, it becomes increasingly more difficult to establish, with any conviction, how correlations between speech rate and memory span should be interpreted. In addition, the evidence suggesting that the planning of articulatory gestures is an important factor in mediating speech rate adds further complexity to the issue.

An area that requires serious consideration in future research is the control of attentional processes in bilinguals. It has been suggested that when two language systems are in competition, responses in one language require the inhibition or suppression of the other: the so-called activation hypothesis (Green, 1995). This view suggests that variation in bilingual performance may be partly mediated by differential costs in suppressing or inhibiting the level of activation between the dominant and less dominant languages. Von Studnitz and Green (1997), for example, found that the cost of switching between language in a language-specific lexical decision task was much reduced when responses could be made without reference to either language. These findings suggest that the bilingual variation memory span could, in part, be mediated by a need to overcome the higher level of activation associated with the dominant language. Moreover, the costs associated with such inhibition processes would be particularly dramatic when the stimuli are language-neutral; as in the case of numerals. Under these circumstances, an interesting set of predictions could be made with regard to the manner in which such putative switch costs interact with language dominance, language of instruction, and trial order factors (i.e. the language order in which memory span measure are taken).

Whilst an account of bilingual processing in terms of altering levels of activation certainly merits attention, this hypothesis was incapable of being tested with the data presented in this thesis. An insensitivity to language switching costs inherent in the memory span procedure makes this an inappropriate paradigm with which to examine such effects. The main source of insensitivity arises from the fact that memory span tasks commence with multiple lists at sub-span levels (typically 1 or 2 items) and are increased incrementally until supra-span lengths are reached and recall becomes impossible. Under such circumstances, even if switch costs are present, it is unlikely that these will be noted as subjects invariably recall the initial items is all lists with 100 per cent accuracy. The effects of language switching on memory capacity in bilinguals predicted by the activation hypothesis, however, could be examined by modifying the procedure such that the language of recall is alternated within the same block of trials.

Although the present findings identified a range of factors that influence bilingual short-term memory processes this in itself was insufficient to understand the complex interrelationships that are likely to exist between these variables. The domain of computational modelling, on the other hand, is well-suited to the detailed examination of such interactions. Recent advances have been made in developing connectionist models of bilingual word recognition (e.g., Dijkstra & van Heuven, in press) and serial recall processes (Brown & Hulme, 1995; Burgess & Hitch, 1992; Henson et al., 1996). The success of these models in simulating human performance suggests that computational modelling is an exciting paradigm with which to tease apart the intricate relationship between these factors to provide a more complete understanding of the determinants of both bilingual and monolingual memory capacity. The experiments presented in this thesis would be a useful source of data with which to model such processes.

Although the central concern of the studies presented here was the examination of the capacity limits and the determinants of bilingual information processing, several findings are relevant to the study of monolingual processing. Of these, the finding that memory span for numerals is greater than for digit words could have some impact upon attempts to specify the role of the working memory system, particularly the central executive component, in the integration and organisation of information.

Since Miller's (1956) seminal work on the capacity limits of human information processing, the concept of chunking has proved a powerful, explanatory principle in terms of the organisational processes that bolster short-term memory, It is generally accepted that chunking depends upon extensive prior long-term knowledge (Ericsson & Chase, 1982; Simon, 1974). Familiar sequences of digits (such as 1066) are, thus, likely to be recalled more efficiently than unfamiliar ones. The impact of chunking and subjective organisation have been examined extensively (e.g., Tulving, 1962. 1966; Tulving & Hastie, 1972) and the findings have demonstrated the powerful effect of semantic associations and categorisation on recall. It should be noted, however, that such studies have generally relied upon the use of free-recall paradigms and, thus, reflect long-term memory processes. The cognitive mechanisms by which the organisation of material is mediated by working memory, on the other hand, are poorly understood.

Lyons (1977), for example, found no evidence to support the view that individual differences in digit span were mediated by factors related to chunking or grouping processes as high and low span individuals benefited to the same degree when instructed to group successive digits in threes. Similarly, Dempster and Zinkgraf (1982) argued that the variation in digit span is unrelated to chunking processes. The findings that memory span for unrelated words is generally poorer than for digits (e.g., Dempster, 1978) and that practice in recalling series of digits increases digit span but does not generalise to other materials (Ericsson, Chase, & Faloon, 1980), however, suggests that the evidence of chunking in digit span tasks reflects specific experience with digits.

One reason for a lack of progress in specifying the precise role and status of chunking within short-term memory is that the standard memory span paradigm (with its emphasis on a rapid rate of presentation) provides little opportunity for chunking to occur (Hunt & Love, 1972) and is, thus, a relatively insensitive measure with which to observe such processes. In addition, the examination of chunking processes in memory span tasks is problematic as the large individual differences observed in such procedures make it impossible to compare performance between subjects directly in meaningful ways.

Chunking processes in short-term memory have, of course, been examined by using fixed-length, serial recall tasks and by manipulating the temporal rate of presentation in ways that encourage chunking (e.g., Broadbent & Broadbent, 1973, 1981). Whilst such procedures generate data that are more readily comparable between subjects, individual differences in memory span create situations where the demands associated with same tasks vary across subjects depending upon whether these happen to be at either supra-, sub- or actual-span levels. One way of circumventing this problem is to screen subjects prior to testing to ensure an equivalence of memory span: this time-consuming alternative, however, does not appear to have been attempted.

The numeral advantage effect, however, provides a potentially interesting window of opportunity with which to explore the role of working memory phenomena in the organisation of material prior to output and an examination of the interface between the long-term and short-term memory systems. In particular, the finding that the pattern of errors between numerals and digit words varies in a manner that is theoretically interpretable in terms of a chunking hypothesis suggests that comparing the processing of symbolic and lexical representations could provide some insight into the role of the memory system in the organisation of information prior to production.

In this respect, the findings of a series of current investigations examining various aspects of the numeral advantage effect are encouraging. We have found, for example, that spatial tapping, a secondary task that interferes with visuo-spatial sketchpad functioning, eliminated the numeral advantage effect. In addition, a more exhaustive analysis of errors made for numerals and digit words by monolinguals was consistent with the findings presented in this thesis and strengthens the claims made herein (Chincotta et al., 1997). Moreover, the finding that the numeral advantage effect persists under both articulatory suppression and concurrent random generation seems a natural starting point from which to examine the role of implicit grouping and explicit memorial strategies in mediating the effect. Further research, for example, could examine the role of the central executive in mediating the hypothesised difference in chunking predisposition or 'chunkability' between symbolic and lexical representations in an attempt to understand the contribution of this relatively poorly understood component of working memory.

An alternative explanation of the superior recall for numerals relative to digit words lies in the notion of a limited capacity visual store within the visuo-spatial sketchpad that is analogous to the phonological loop. To this end, the role of a limited capacity visual storage system and the effects of visual length and the speed of perceptual processing are being investigated by examining the related letter advantage effect: the finding that memory span for letters, such as r, t, & u, is larger than letter triplets, such as rrr, ttt, & uuu, which, in turn, is greater than for word equivalents in terms of articulation time, such as are, tea, & you, (Chincotta, Jarrold, & Baddeley, in preparation).

The finding that the effect of output delay on memory performance varied as a function of word frequency was important for both the bilingual and monolingual research literatures. As far as monolingual memory span is concerned, this finding contributed toward resolving the problems associated with a strong form of the output delay hypothesis and the effect of articulatory suppression on memory performance. Namely, if output delay is an important factor mediating memory span, why is the word length abolished under articulatory suppression? The present findings demonstrated that when the strength of long-term memory representations was weak (as with low frequency words) the redintegrative process is rendered less efficient compared to high frequency words. Under these circumstances, short-term memory performance was principally mediated by the temporal capacity of the phonological store. When the strength of long-term memory representations is strong, however, the additional support from long-term memory reduces the importance the temporal constraints of the phonological store. This view suggested that findings in which articulatory suppression fails to eliminate a memory span advantage for high frequency items compared to low frequency ones (Gregg et al., 1989) could be partly explained by a variation in the effect of output delay between the items.

If the interpretation of these findings is correct, studies that examine the relationship between articulatory suppression, output delay and word frequency could potentially allow a more precise specification of the parameters that mediate memory span. It seems appropriate to argue for a greater recognition of the multiplicity of factors that combine to modulate the capacity limits of the human information processing system and the specific need for the development of a unified model of memory processing that takes a wider range of variables into account.

The present findings indicated that articulatory suppression had discrete effects on digit span depending upon whether the stimuli are represented as numerals or digit words. Moreover, the finding that the relationship between speed of perceptual processing task and response latency for numerals was equivalent between the dominant and less dominant languages of Greek-English bilinguals raises some interesting questions with regard to the representational status of language-neutral stimuli in the bilingual lexicon. Such questions could be addressed within the literature on cognate and non cognate mental representations in bilinguals (e.g., de Groot & Nas, 1991).

It would be remiss to omit in this summary chapter some consideration of the implications of the present findings for bilingual research in general. Although the present studies were largely confined to an examination of bilingual memory capacity, several findings could be helpful to other paradigms concerned with other aspects of bilingual processing. As already stated, the finding that output delay may be one influential determinant of bilingual memory span suggested that bilingual research paradigms that require verbal responses should pay consideration to the potential effects of output. In addition, the finding that numeral reading time was sensitive to language dominance might prove a useful, rough and ready measure of the level of relative proficiency between the languages of bilinguals. We are at present conducting a study in which the sensitivity of numeral reading time in quantifying bilingual proficiency is being evaluated by comparing performance on this task to other, established, measures of bilingualism such as expressive and productive vocabulary (Chincotta & Adlam, in preparation).

The application of eye-tracking techniques, and pupilometry in particular, to the examination of bilingual information processing is a potentially productive means of examining cognitive loads that are independent of overt articulation. The eye tracking study presented in this thesis required subjects to read aloud, thus, a logical next step is to study phonological encoding among bilinguals in a task where phonological encoding might be avoided or is at least not absolutely necessary. We are, therefore, replicating these findings under silent reading conditions. Further plans include the examination of processing loads and reading performance during reading span tasks (e.g., Daneman & Carpenter, 1980).

Since the pioneering work of Ebbinghaus in 1885 (published in 1913) digit span has been a consistent feature of formal assessments of intelligence. The relationship between short-term memory capacity and a range of human intellectual performance such as the acquisition of reading skills, arithmetic skills, and second language acquisition, to name but a few, are well-documented. These strong and consistent, even if not always understood, relationships are proof positive of the importance of a mental workspace capable of storing information in the development of cognitive abilities.

There is a pressing need, however, to examine whether the relationship between memory span and cognitive performance extends to bilinguals in situations where these individuals are required to perform in the less dominant language. This thesis highlighted the fact that children schooled in a language other than the language of the home had lower digit spans compared to peers schooled in the language of the home. This finding suggests that bilingual children may be disadvantaged in a range of cognitive tasks involving the processing of digits (Hoosain & Sallili, 1988). An empirical test of this hypothesis would be of value in terms of furthering our understanding of the possible disadvantages in bilingual education as and would go some way toward establishing the ecological validity of bilingual memory span measures.

Finally, the examination of the determinants of bilingual memory capacity has proved to be a richer and more complex area of inquiry than originally anticipated. The recognition that explanations of the variation in bilingual short-term memory performance based on a relatively simple account of working memory theory are inappropriate brings the bilingual digit span effect into line with current understanding of the factors that modulate performance in monolinguals. The work presented here has demonstrated the value of applying models of monolingual processing to bilingual functioning as such research endeavour is occasionally capable of extending understanding of human mental performance.

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APPENDIX 1

SUMMARY ANOVA TABLES FOR EXPERIMENT 1

1.1

Summary Analysis of Variance Table for self-rating data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	15.922	3	5.307	4.961	0.0038
B (LANGUAGE)	6.169	1	6.169	25.091	0.0000
AB	48.085	3	16.028	65.193	0.0000
Between Error	64.189	60	1.070		
(Error BxS)	14.752	60	0.246		

1.2

Summary Analysis of Variance Table for numeral reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (MOTHER-T)	190.125	1	190.125	0.537	0.4664
B (SCHOOL)	561.125	1	561.125	1.586	0.2128
C (LANGUAGE)	30.031	1	30.031	0.848	0.3607
AB	3.781	1	3.781	0.011	0.9180
AC	1682.000	1	1682.000	47.516	0.0000
BC	1512.500	1	1512.500	42.727	0.0000
ABC	2.531	1	2.531	0.072	0.7901
Between Error	21226.938	60	353.782		
(Error CxS)	2123.938	60	35.399		

1.2:1

Summary Analysis of Variance Table for numeral reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	755.031	3	251.677	0.711	0.5490
B (LANGUAGE)	30.031	1	30.031	0.848	0.3607
AB	3197.031	3	1065.677	30.105	0.0000
Between Error	21226.938	60	353.782		
(Error BxS)	2123.938	60	35.399		

1.3
Summary Analysis of Variance Table for digit span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (MOTHER-T)	1.758	1	1.758	0.923	0.3406
B (SCHOOL)	0.008	1	0.008	0.004	0.9491
C (LANGUAGE)	0.383	1	0.383	0.784	0.3793
AB	0.070	1	0.070	0.037	0.8483
AC	4.133	1	4.133	8.469	0.0051
BC	10.695	1	10.695	21.916	0.0000
ABC	0.008	1	0.008	0.016	0.8997
Between Error	114.281	60	1.905		
(Error CxS)	29.281	60	0.488		

1.3:1
Summary Analysis of Variance Table for digit span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	1.836	3	0.612	0.321	0.8099
B (LANGUAGE)	0.383	1	0.383	0.784	0.3793
AB	14.836	3	4.945	10.133	0.0000
Between Error	114.281	60	1.905		
(Error BxS)	29.281	60	0.488		

1.4
Summary Analysis of Variance Table for suppressed digit span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (MOTHER-T)	0.383	1	0.383	0.307	0.5817
B (SCHOOL)	0.945	1	0.945	0.758	0.3875
C (LANGUAGE)	0.945	1	0.945	1.767	0.1888
AB	0.383	1	0.383	0.307	0.5817
AC	0.383	1	0.383	0.716	0.4009
BC	0.008	1	0.008	0.015	0.9042
ABC	0.070	1	0.070	0.131	0.7182
Between Error	74.844	60	1.247		
(Error CxS)	32.094	60	0.535		

1.5
Summary Analysis of Variance Table for reading time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	64.800	1	64.800	0.138	0.7195
B (LANGUAGE)	16.200	1	16.200	0.612	0.4564
AB	24.200	1	24.200	0.915	0.3668
Between Error	3744.400	8	468.050		
(Error BxS)	211.600	8	26.450		

1.6
Summary Analysis of Variance Table for digit span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	0.200	1	0.200	0.091	0.7707
B (LANGUAGE)	1.800	1	1.800	6.000	0.0400
AB	0.800	1	0.800	2.667	0.1411
Between Error	17.600	8	2.200		
(Error BxS)	2.400	8	0.300		

1.7
Summary Analysis of Variance Table for numeral and digit word reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	546.898	3	182.299	0.967	0.4143
B (LANGUAGE)	2389.133	1	2389.133	137.706	0.0000
AB	331.398	3	110.466	6.367	0.0008
Between Error	11312.219	60	188.537		
(Error BxS)	1040.969	60	17.349		

SUMMARY ANOVA TABLES FOR EXPERIMENT 2

2.1

Summary Analysis of Variance Table for numeral reading time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	1655.249	8	206.906	50.705	0.0000
B (BILING-TYPE)	42.773	1	42.773	10.482	0.0014
C (LANGUAGE)	209.982	1	209.982	131.206	0.0000
AB	26.118	8	3.265	0.800	0.6032
AC	25.493	8	3.187	1.991	0.0497
BC	101.691	1	101.691	63.541	0.0000
ABC	41.975	8	5.247	3.278	0.0016
Between Error	758.994	186	4.081		
(Error CxS)	297.675	186	1.600		

2.2

Summary Analysis of Variance Table for FS numeral reading time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	6.993	8	0.874	27.834	0.0000
B (BILING-TYPE)	0.097	1	0.097	42.066	0.0000
AB	0.028	8	0.003	1.495	0.1694
Between Error	2.921	93	0.031		
(Error BxS)	0.215	93	0.002		

2.3

Summary Analysis of Variance Table for SS numeral reading time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	9.820	8	1.228	24.450	0.0000
B (LANGUAGE)	3.020	1	3.020	101.671	0.0000
AB	0.647	8	0.081	2.723	0.0096
Between Error	4.669	93	0.050		
(Error BxS)	2.762	93	0.030		

2.4
Summary Analysis of Variance Table - for digit word reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	2501.267	8	312.658	40.390	0.0000
B (BILING-TYPE)	9.580	1	9.580	1.238	0.2674
C (LANGUAGE)	120.905	1	120.905	224.381	0.0000
AB	3.745	8	0.468	0.060	0.9999
AC	66.204	8	8.276	15.358	0.0000
BC	2.550	1	2.550	4.733	0.0308
ABC	3.199	8	0.400	0.742	0.6542
Between Error	1439.832	186	7.741		
(Error CxS)	100.224	186	0.539		

2.5
Summary Analysis of Variance Table for FS digit word reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	1182.736	8	147.842	15.478	0.0000
B (LANGUAGE)	44.168	1	44.168	97.902	0.0000
AB	32.712	8	4.089	9.064	0.0000
Between Error	888.337	93	9.552		
(Error BxS)	41.956	93	0.451		

2.6
Summary Analysis of Variance Table for SS digit word reading data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	1322.275	8	165.284	27.872	0.0000
B (LANGUAGE)	79.288	1	79.288	126.549	0.0000
AB	36.691	8	4.586	7.320	0.0000
Between Error	551.495	93	5.930		
(Error BxS)	58.268	93	0.627		

2.7

Summary Analysis of Variance Table for articulation time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	1955199.093	8	244399.887	23.609	0.0000
B (BILING-TYPE)	139136.916	1	139136.916	13.440	0.0003
C (LANGUAGE)	1308018.460	1	1308018.460	636.055	0.0000
AB	57733.777	8	7216.722	0.697	0.6938
AC	16742.511	8	2092.814	1.018	0.4242
BC	304558.398	1	304558.398	148.099	0.0000
ABC	41569.672	8	5196.209	2.527	0.0124
Between Error	1925504.378	186	10352.174		
(Error CxS)	382500.324	186	2056.453		

2.8

Summary Analysis of Variance Table for digit span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	126.855	8	15.857	11.878	0.0000
B (BILING-TYPE)	0.217	1	0.217	0.163	0.6873
C (LANGUAGE)	27.809	1	27.809	65.730	0.0000
AB	9.556	8	1.195	0.895	0.5220
AC	4.953	8	0.619	1.464	0.1731
BC	15.901	1	15.901	37.585	0.0000
ABC	3.722	8	0.465	1.100	0.3652
Between Error	248.300	186	1.335		
(Error CxS)	78.692	186	0.423		

SUMMARY ANOVA TABLES FOR EXPERIMENT 3

3.1
Summary Analysis of Variance Table for articulation time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	232853.362	1	232853.362	13.728	0.0004
B (BILING-TYPE)	90117.150	2	45058.575	2.657	0.0777
C (LANGUAGE)	736632.461	1	736632.461	312.188	0.0000
D(WORD-LENGTH)	2484708.118	1	2484708.118	866.689	0.0000
AB	4757.339	2	2378.670	0.140	0.8694
AC	34834.251	1	34834.251	14.763	0.0003
AD	83100.302	1	83100.302	28.986	0.0000
BC	471961.496	2	235980.748	100.010	0.0000
BD	26067.569	2	13033.785	4.546	0.0141
CD	256559.260	1	256559.260	153.727	0.0000
ABC	830.226	2	415.113	0.176	0.8391
ABD	793.761	2	396.881	0.138	0.8710
ACD	13679.614	1	13679.614	8.197	0.0056
BCD	72336.441	2	36168.220	21.672	0.0000
ABCD	3401.106	2	1700.553	1.019	0.3666
Between Error	1119458.760	66	16961.496		
(Error CxS)	155732.084	66	2359.577		
(Error DxS)	189215.144	66	2866.896		
(Error CDxS)	110149.130	66	1668.926		

3.2
Summary Analysis of Variance Table for memory span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	4.253	1	4.253	2.413	0.1251
B (BILING-TYPE)	6.377	2	3.188	1.809	0.1719
C (LANGUAGE)	1.125	1	1.125	4.427	0.0392
D(WORD-LENGTH)	19.014	1	19.014	42.873	0.0000
AB	0.731	2	0.365	0.207	0.8133
AC	0.087	1	0.087	0.342	0.5609
AD	0.087	1	0.087	0.196	0.6596
BC	16.818	2	8.409	33.092	0.0000
BD	1.533	2	0.766	1.728	0.1855
CD	0.056	1	0.056	0.168	0.6830
ABC	0.950	2	0.475	1.869	0.1624
ABD	0.845	2	0.423	0.953	0.3907
ACD	0.031	1	0.031	0.095	0.7593
BCD	0.648	2	0.324	0.981	0.3805
ABCD	0.224	2	0.112	0.339	0.7136
Between Error	116.333	66	1.763		
(Error CxS)	16.771	66	0.254		
(Error DxS)	29.271	66	0.443		
(Error CDxS)	21.792	66	0.330		

SUMMARY ANOVA TABLES FOR EXPERIMENT 4

4.1
Summary Analysis of Variance Table for articulation time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	152495.784	1	152495.784	3.586	0.0627
B (BILING-TYPE)	157954.917	2	78977.458	1.857	0.1642
C (LANGUAGE)	2354156.155	1	2354156.155	477.047	0.0000
D(WORD-LENGTH)	6832171.641	1	6832171.641	951.178	1.0000
AB	62264.389	2	31132.195	0.732	0.4848
AC	23334.750	1	23334.750	4.729	0.0333
AD	20797.376	1	20797.376	2.895	0.0935
BC	192571.720	2	96285.860	19.511	0.0000
BD	58313.909	2	29156.954	4.059	0.0217
CD	144570.727	1	144570.727	39.945	0.0000
ABC	3631.671	2	1815.835	0.368	0.6936
ABD	43699.413	2	21849.706	3.042	0.0545
ACD	296.309	1	296.309	0.082	0.7757
BCD	6588.168	2	3294.084	0.910	0.4075
ABCD	15203.969	2	7601.985	2.100	0.1305
Between Error	2806748.379	66	42526.491		
(Error CxS)	325700.333	66	4934.854		
(Error DxS)	474068.399	66	7182.855		
(Error CDxS)	238869.440	66	3619.234		

4.2
Summary Analysis of Variance Table for memory span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (GRADE)	27.813	1	27.813	24.420	0.0000
B (BILING-TYPE)	0.924	2	0.462	0.405	0.6683
C (LANGUAGE)	26.584	1	26.584	115.014	0.0000
D(WORD-LENGTH)	57.334	1	57.334	198.888	0.0000
AB	1.174	2	0.587	0.515	0.5998
AC	0.022	1	0.022	0.094	0.7603
AD	0.195	1	0.195	0.678	0.4134
BC	6.194	2	3.097	13.400	0.0000
BD	2.382	2	1.191	4.131	0.0204
CD	7.188	1	7.188	21.745	0.0000
ABC	0.132	2	0.066	0.285	0.7526
ABD	0.000	2	0.000	0.000	1.0000
ACD	0.070	1	0.070	0.213	0.6462
BCD	0.924	2	0.462	1.397	0.2546
ABCD	1.188	2	0.594	1.796	0.1740
Between Error	75.172	66	1.139		
(Error CxS)	15.255	66	0.231		
(Error DxS)	19.026	66	0.288		
(Error CDxS)	21.818	66	0.331		

SUMMARY ANOVA TABLES FOR EXPERIMENT 5

5.1

Summary Analysis of Variance Table for gaze duration data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	67347.329	1	67347.329	11.968	0.0016
B (LANGUAGE)	5094.685	1	5094.685	2.428	0.1297
AB	137742.667	1	137742.667	65.643	0.0000
Between Error	168817.879	30	5627.263		
(Error BxS)	62950.588	30	2098.353		

5.2

Summary Analysis of Variance Table for percentage fixation data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	213.891	1	213.891	0.296	0.5907
B (LANGUAGE)	1550.391	1	1550.391	8.466	0.0068
AB	2437.891	1	2437.891	13.312	0.0010
Between Error	21708.969	30	723.632		
(Error BxS)	5494.219	30	183.141		

5.3

Summary Analysis of Variance Table for articulation time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	27459.252	1	27459.252	3.936	0.0565
B (LANGUAGE)	96729.639	1	96729.639	133.131	0.0000
AB	29046.574	1	29046.574	39.977	0.0000
Between Error	209307.682	30	6976.923		
(Error BxS)	21797.225	30	726.574		

5.4
Summary Analysis of Variance Table for reading time data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	1918.878	1	1918.878	16.884	0.0003
B (LANGUAGE)	0.319	1	0.319	0.007	0.9328
AB	2734.767	1	2734.767	61.973	0.0000
Between Error	3409.469	30	113.649		
(Error BxS)	1323.849	30	44.128		

5.5
Summary Analysis of Variance Table for memory span data
Mixed Design (alias Split Plot)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
A (BILING-TYPE)	5.641	1	5.641	3.017	0.0927
B (LANGUAGE)	4.000	1	4.000	5.598	0.0246
AB	14.062	1	14.062	19.679	0.0001
Between Error	56.094	30	1.870		
(Error BxS)	21.438	30	0.715		

SUMMARY ANOVA TABLES FOR EXPERIMENT 6

6.1

Summary Analysis of Variance Table for reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.144	19	0.008		
A (LANGUAGE)	0.130	1	0.130	72.877	0.0000
(Error AxS)	0.034	19	0.002		
B (ITEM)	0.055	1	0.055	53.715	0.0000
(Error BxS)	0.019	19	0.001		
AB	0.036	1	0.036	29.844	0.0000
(Error ABxS)	0.023	19	0.001		

6.2

Summary Analysis of Variance Table for memory span data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	56.284	19	2.962		
A (LANGUAGE)	7.503	1	7.503	13.998	0.0014
(Error AxS)	10.184	19	0.536		
B (ITEM)	2.278	1	2.278	9.290	0.0066
(Error BxS)	4.659	19	0.245		
AB	0.003	1	0.003	0.005	0.9456
(Error ABxS)	12.434	19	0.654		

SUMMARY ANOVA TABLES FOR EXPERIMENT 7

7.1

Summary Analysis of Variance Table for reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.060	15	0.004		
A (LANGUAGE)	0.057	1	0.057	68.696	0.0000
(Error AxS)	0.013	15	0.001		
B (ITEM)	0.026	1	0.026	62.740	0.0000
(Error BxS)	0.006	15	0.000		
AB	0.016	1	0.016	32.815	0.0000
(Error ABxS)	0.007	15	0.000		

7.2

Summary Analysis of Variance Table for memory span data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	42.389	15	2.826		
A (ITEM)	11.580	1	11.580	31.151	0.0001
(Error AxS)	5.576	15	0.372		
B (LANGUAGE)	5.908	1	5.908	9.988	0.0065
(Error BxS)	8.873	15	0.592		
C (SUPPRESSION)	68.299	1	68.299	66.171	0.0000
(Error CxS)	15.482	15	1.032		
AB	0.002	1	0.002	0.003	0.9576
(Error ABxS)	10.029	15	0.669		
AC	0.158	1	0.158	0.267	0.6126
(Error ACxS)	8.873	15	0.592		
BC	0.049	1	0.049	0.120	0.7339
(Error BCxS)	6.107	15	0.407		
ABC	1.221	1	1.221	2.548	0.1313
(Error ABCxS)	7.186	15	0.479		

SUMMARY ANOVA TABLES FOR EXPERIMENT 8

8.1

Summary Analysis of Variance Table for articulation time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.084	35	0.002		
A (LANGUAGE)	0.014	1	0.014	25.005	0.0000
(Error AxS)	0.019	35	0.001		

8.2

Summary Analysis of Variance Table for numeral and digit word reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.191	35	0.005		
A (ITEM)	0.077	1	0.077	99.262	0.0000
(Error AxS)	0.027	35	0.001		
B (LANGUAGE)	0.144	1	0.144	165.576	0.0000
(Error BxS)	0.031	35	0.001		
AB	0.070	1	0.070	112.570	0.0000

8.3

Summary Analysis of Variance Table for numeral and digit word memory span data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	147.891	35	4.225		
A (LANGUAGE)	9.042	1	9.042	11.048	0.0021
(Error AxS)	28.645	35	0.818		
B (RECALL COND)	814.719	2	407.359	379.201	0.0000
(Error BxS)	75.198	70	1.074		
C (ITEM)	9.630	1	9.630	11.468	0.0018
(Error CxS)	29.391	35	0.840		
AB	3.383	2	1.692	2.880	0.0628
(Error ABxS)	41.117	70	0.587		
AC	5.005	1	5.005	10.882	0.0022
(Error ACxS)	16.099	35	0.460		
BC	1.385	2	0.693	1.020	0.3658
(Error BCxS)	47.531	70	0.679		
ABC	0.253	2	0.127	0.233	0.7928
(Error ABCxS)	38.080	70	0.544		

8.4
Summary Analysis of Variance Table for numeral and digit word error data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.539	35	0.015		
A (ITEM)	0.038	1	0.038	2.157	0.1509
(Error AxS)	0.610	35	0.017		
B (LANGUAGE)	0.006	1	0.006	0.475	0.4952
(Error BxS)	0.435	35	0.012		
C (RECALL COND)	0.719	2	0.360	24.215	0.0000
(Error CxS)	1.040	70	0.015		
D (ERROR TYPE)	22.854	3	7.618	177.327	0.0000
(Error DxS)	4.511	105	0.043		
AB	0.000	1	0.000	0.003	0.9547
(Error ABxS)	0.588	35	0.017		
AC	0.038	2	0.019	1.295	0.2804
(Error ACxS)	1.023	70	0.015		
AD	0.213	3	0.071	2.481	0.0650
(Error ADxS)	3.002	105	0.029		
BC	0.066	2	0.033	2.066	0.1343
(Error BCxS)	1.110	70	0.016		
BD	0.047	3	0.016	0.523	0.6671
(Error BDxS)	3.138	105	0.030		
CD	1.443	6	0.240	8.441	0.0000
(Error CDxS)	5.981	210	0.028		
ABC	0.000	2	0.000	0.004	0.9960
(Error ABCxS)	0.966	70	0.014		
ABD	0.024	3	0.008	0.296	0.8286
(Error ABDxS)	2.784	105	0.027		
ACD	0.238	6	0.040	1.142	0.3389
(Error ACDxS)	7.280	210	0.035		
BCD	0.125	6	0.021	0.592	0.7364
(Error BCDxS)	7.372	210	0.035		
ABCD	0.117	6	0.020	0.686	0.6611
(Error ABCDxS)	5.969	210	0.028		

8.5
Summary Analysis of Variance Table for playing card memory span data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	52.440	35	1.498		
A (language)	9.375	1	9.375	22.183	0.0000
(Error AxS)	14.792	35	0.423		
B (recall con)	300.905	2	150.453	198.045	0.0000
(Error BxS)	53.178	70	0.760		
AB	6.021	2	3.010	7.933	0.0008
(Error ABxS)	26.563	70	0.379		

8.6
Summary Analysis of Variance Table for playing card error data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.717	35	0.020		
A (LANGUAGE)	0.026	1	0.026	2.376	0.1322
(Error AxS)	0.380	35	0.011		
B (RECALL COND)	0.192	2	0.096	7.206	0.0014
(Error BxS)	0.933	70	0.013		
C (ERROR TYPE)	7.608	3	2.536	65.098	0.0000
(Error CxS)	4.090	105	0.039		
AB	0.007	2	0.004	0.235	0.7909
(Error ABxS)	1.061	70	0.015		
AC	0.204	3	0.068	1.955	0.1253
(Error ACxS)	3.660	105	0.035		
BC	0.954	6	0.159	4.182	0.0005
(Error BCxS)	7.985	210	0.038		
ABC	0.051	6	0.008	0.321	0.9256
(Error ABCxS)	5.532	210	0.026		

SUMMARY ANOVA TABLES FOR EXPERIMENT 9

9:1

Summary Analysis of Variance Table for Greek item identification time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	1241845.33	23	53993.275		
A (ITEM)	72820.167	1	72820.167	33.956	0.0000
(Error AxS)	49323.833	23	2144.514		
B (CONGRUENCY)	151050.667	1	151050.667	68.382	0.0000
(Error BxS)	50805.333	23	2208.928		
AB	541.500	1	541.500	0.322	0.0000
(Error ABxS)	38660.500	23	1680.891		

9:2

Summary Analysis of Variance Table for English item identification time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	1227323.240	23	53361.88		
A (ITEM)	70362.510	1	70362.510	34.287	0.0000
(Error AxS)	47200.240	23	2052.184		
B (CONGRUENCY)	43477.594	1	43477.594	12.979	0.0000
(Error BxS)	77047.156	23	3349.876		
AB	4387.510	1	4387.510	4.703	0.0407
(Error ABxS)	21455.240	23	932.837		

9:3

Summary Analysis of Variance Table for reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	3479.643	23	151.289		
A (LANGUAGE)	80.063	1	80.063	8.108	0.0091
(Error AxS)	227.110	23	9.874		
B (ITEM)	1.683	1	1.683	0.135	0.7168
(Error BxS)	286.985	23	12.478		
AB	108.864	1	108.864	11.196	0.0028
(Error ABxS)	223.641	23	9.724		

9:4

Summary Analysis of Variance Table for memory span data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	183.492	23	7.978		
A (LANGUAGE)	3.897	1	3.897	6.181	0.0206
(Error AxS)	14.499	23	0.630		
B (ITEM)	11.883	1	11.883	29.505	0.0000
(Error BxS)	9.263	23	0.403		
C(RECALL COND)	516.578	2	258.289	164.340	0.0000
(Error CxS)	4.090	46	0.039		
AB	3.022	1	3.022	6.699	0.0164
(Error ABxS)	10.374	23	0.451		
AC	3.283	2	1.641	2.097	0.1344
(Error ACxS)	36.009	46	0.783		
BC	0.255	2	0.128	0.269	0.7650
(Error BCxS)	21.786	46	0.474		
ABC	1.002	2	0.501	0.876	0.4231
(Error ABCxS)	26.290	46	0.572		

SUMMARY ANOVA TABLES FOR EXPERIMENT 10

10:1

Summary Analysis of Variance Table for articulation time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	173753.818	15	11583.588		
A (LANGUAGE)	75304.507	1	75304.507	51.525	0.0000
(Error AxS)	21922.715	15	1461.514		
B(WORD-LENGTH)	180979.340	1	180979.340	130.006	0.0000
(Error BxS)	20881.215	15	1392.081		
AB	16694.793	1	16694.793	14.323	0.0018
(Error ABxS)	17483.457	15	1165.564		

10:2

Summary Analysis of Variance Table for reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	45593.209	15	3039.547		
A (LANGUAGE)	83088.062	1	83088.062	176.184	0.0000
(Error AxS)	7073.963	15	471.598		
B(WORD-LENGTH)	58806.250	1	58806.250	133.147	0.0000
(Error BxS)	6624.955	15	441.664		
AB	2000.326	1	2000.326	8.922	0.0092
(Error ABxS)	3362.969	15	224.198		

10:3
Summary Analysis of Variance Table for forward recall data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	6.892	15	0.459		
A (LANGUAGE)	1.727	1	1.727	16.428	0.0010
(Error AxS)	1.577	15	0.105		
B (FIRST-HALF)	0.317	1	0.317	3.058	0.1008
(Error BxS)	1.556	15	0.104		
C (SECOND-HALF)	0.413	1	0.413	8.270	0.0115
(Error CxS)	0.748	15	0.050		
D (POSITION)	5.375	4	1.344	18.518	0.0000
(Error DxS)	4.354	60	0.073		
AB	0.002	1	0.002	0.048	0.8290
(Error ABxS)	0.758	15	0.051		
AC	0.043	1	0.043	0.815	0.3810
(Error ACxS)	0.793	15	0.053		
AD	0.115	4	0.029	0.906	0.4662
(Error ADxS)	1.901	60	0.032		
BC	0.000	1	0.000	0.002	0.9668
(Error BCxS)	0.817	15	0.054		
BD	0.050	4	0.013	0.419	0.7941
(Error BDxS)	1.803	60	0.030		
CD	0.131	4	0.033	1.535	0.2035
(Error CDxS)	1.279	60	0.021		
ABC	0.340	1	0.340	5.426	0.0342
(Error ABCxS)	0.940	15	0.063		
ABD	0.098	4	0.024	0.872	0.4863
(Error ABDxS)	1.680	60	0.028		
ACD	0.209	4	0.052	1.551	0.1991
(Error ACDxS)	2.025	60	0.034		
BCD	0.047	4	0.012	0.423	0.7912
(Error BCDxS)	1.675	60	0.028		
ABCD	0.069	4	0.017	0.716	0.5844
(Error ABCDxS)	1.441	60	0.024		

10:4
Summary Analysis of Variance Table for backward recall data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	8.062	15	0.537		
A (LANGUAGE)	0.127	1	0.127	1.816	0.1978
(Error AxS)	1.045	15	0.070		
B (FIRST-HALF)	0.506	1	0.506	7.764	0.0138
(Error BxS)	0.978	15	0.065		
C (SECOND-HALF)	0.032	1	0.032	0.325	0.5769
(Error CxS)	1.459	15	0.097		
D (POSITION)	6.348	4	1.587	16.307	0.0000
(Error DxS)	5.839	60	0.097		
AB	0.019	1	0.019	0.342	0.5675
(Error ABxS)	0.840	15	0.056		
AC	0.002	1	0.002	0.014	0.9078
(Error ACxS)	1.689	15	0.113		
AD	0.162	4	0.040	1.275	0.2900
(Error ADxS)	1.901	60	0.032		
BC	0.306	1	0.306	5.424	0.0342
(Error BCxS)	0.847	15	0.056		
BD	0.213	4	0.053	2.127	0.0884
(Error BDxS)	1.505	60	0.025		
CD	0.081	4	0.020	0.939	0.4475
(Error CDxS)	1.288	60	0.021		
ABC	0.172	1	0.172	1.854	0.1934
(Error ABCxS)	1.393	15	0.093		
ABD	0.038	4	0.010	0.371	0.8283
(Error ABDxS)	1.555	60	0.026		
ACD	0.066	4	0.016	0.847	0.5009
(Error ACDxS)	1.165	60	0.019		
BCD	0.154	4	0.038	1.581	0.1911
(Error BCDxS)	1.459	60	0.024		
ABCD	0.079	4	0.020	0.947	0.4431
(Error ABCDxS)	1.246	60	0.021		

SUMMARY ANOVA TABLES FOR EXPERIMENT 11

11:1

Summary Analysis of Variance Table for articulation time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	177163.587	15	11810.906		
A (LANGUAGE)	427579.761	1	427579.761	144.397	0.0000
(Error AxS)	44417.204	15	2961.147		
B(WORD-LENGTH)	81569.740	1	81569.740	77.820	0.0000
(Error BxS)	15722.697	15	1048.180		
AB	698.941	1	698.941	1.127	0.3053
(Error ABxS)	9305.829	15	620.389		

11:2

Summary Analysis of Variance Table for reading time data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	0.095	15	0.006		
A (LANGUAGE)	0.183	1	0.183	125.478	0.0000
(Error AxS)	0.022	15	0.001		
B(WORD-LENGTH)	0.059	1	0.059	66.537	0.0000
(Error BxS)	0.013	15	0.001		
AB	0.010	1	0.010	27.514	0.0001
(Error ABxS)	0.006	15	0.000		

11:3
Summary Analysis of Variance Table for forward recall data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	8.001	15	0.533		
A (LANGUAGE)	1.693	1	1.693	26.539	0.0001
(Error AxS)	0.957	15	0.064		
B (FIRST-HALF)	0.247	1	0.247	2.261	0.1534
(Error BxS)	1.641	15	0.109		
C (SECOND-HALF)	0.002	1	0.002	0.042	0.8403
(Error CxS)	0.651	15	0.043		
D (POSITION)	8.059	4	2.015	30.026	0.0000
(Error DxS)	4.026	60	0.067		
AB	0.474	1	0.474	7.283	0.0165
(Error ABxS)	0.977	15	0.065		
AC	0.038	1	0.038	0.730	0.4062
(Error ACxS)	0.777	15	0.052		
AD	0.359	4	0.090	3.759	0.0086
(Error ADxS)	1.432	60	0.024		
BC	0.241	1	0.241	4.550	0.0499
(Error BCxS)	0.795	15	0.053		
BD	0.094	4	0.024	0.603	0.6618
(Error BDxS)	2.345	60	0.039		
CD	0.068	4	0.017	0.649	0.6297
(Error CDxS)	1.574	60	0.026		
ABC	0.086	1	0.086	0.729	0.4067
(Error ABCxS)	1.770	15	0.118		
ABD	0.337	4	0.084	3.261	0.0174
(Error ABDxS)	1.549	60	0.026		
ACD	0.385	4	0.096	2.719	0.0378
(Error ACDxS)	2.126	60	0.035		
BCD	0.053	4	0.013	0.571	0.6845
(Error BCDxS)	1.394	60	0.023		
ABCD	0.117	4	0.029	0.714	0.5859
(Error ABCDxS)	2.455	60	0.041		

11:4
Summary Analysis of Variance Table for backward recall data
Within Subjects Design (alias Randomized Blocks)

Source of Variation	Sum of Squares	df	Mean Squares	F	p
Subjects	10.025	15	0.668		
A (LANGUAGE)	0.819	1	0.819	7.977	0.0128
(Error AxS)	1.541	15	0.103		
B (FIRST-HALF)	0.041	1	0.041	0.313	0.5840
(Error BxS)	1.947	15	0.130		
C (SECOND-HALF)	0.147	1	0.147	2.306	0.1497
(Error CxS)	0.956	15	0.064		
D (POSITION)	9.355	4	2.339	29.947	0.0000
(Error DxS)	4.686	60	0.078		
AB	0.338	1	0.338	6.187	0.0251
(Error ABxS)	0.819	15	0.055		
AC	0.172	1	0.172	1.760	0.2044
(Error ACxS)	1.468	15	0.098		
AD	0.268	4	0.067	2.763	0.0355
(Error ADxS)	1.453	60	0.024		
BC	0.019	1	0.019	0.225	0.6418
(Error BCxS)	1.274	15	0.085		
BD	0.040	4	0.010	0.277	0.8916
(Error BDxS)	2.159	60	0.036		
CD	0.246	4	0.062	1.592	0.1882
(Error CDxS)	2.322	60	0.039		
ABC	0.124	1	0.124	2.308	0.1495
(Error ABCxS)	0.804	15	0.054		
ABD	0.113	4	0.028	1.171	0.3327
(Error ABDxS)	1.442	60	0.024		
ACD	0.086	4	0.022	0.545	0.7035
(Error ACDxS)	2.380	60	0.040		
BCD	0.110	4	0.027	1.051	0.3888
(Error BCDxS)	1.568	60	0.026		
ABCD	0.112	4	0.028	1.335	0.2675
(Error ABCDxS)	1.256	60	0.021		

APPENDIX 2

2.1: Digit words (IPA) and number of syllables for digits in Finnish and Swedish for Experiments 1, 2, & 5.

	Finnish			Swedish		
Digit	Word	IPA	Syllables	Word	IPA	Syllables
1	yksi	'yksi	2	ett	ɛt:	1
2	kaksi	'kaksi	2	två	tvo:	1
3	kolme	'kɔlmɛ	2	tre	tre:	1
4	neljä	'nɛljæ	2	fyra	'fy:ra	2
5	viisi	'vi:si	2	fem	fɛm:	1
6	kuusi	'ku:si	2	sex	sɛks	1
7	seitsemän	'sɛitsɛmæn	3	sju	ʃu:	1
8	kahdeksan	'kahdɛksan	3	åtta	'ɔt:a	1
9	yhdeksän	'yhdɛksæn	3	nio	'ni:u	1
Mean			2.33			1.11

2.2: Finnish short and long words used in Experiment 3

Short words			Long words		
Item	Frequency per million	English equivalent	Item	Frequency per million	English equivalent
jää	83	ice	hedelmä	80	fruit
kuu	108	moon	paperi	115	paper
tee	30	tea	sipuli	33	onion
maa	2015	earth	ihminen	1893	human
säe	18	verse	osoite	19	address
yö	305	night	tavara	278	object
suo	123	swamp	aurinko	230	sun
voi	65	butter	peruna	55	potato
Mean	343.38			341.5	

2.3: Swedish short and long words used in Experiment 3

Short words			Long words		
Item	Frequency per million	English equivalent	Item	Frequency per million	English equivalent
regn	28	rain	gräsmatta	29	lawn
sak	453	thing	regering	387	government
par	427	pair	område	398	district
krig	264	war	utställning	233	exhibition
bild	474	picture	arbete	512	work
eld	55	fire	semester	52	holiday
bok	876	book	människa	844	man
mat	93	food	innehåll	98	contents
Mean	335			318.13	

2.4: Finnish and Swedish short and long nonwords used in Experiment 4

Finnish nonwords		Swedish nonwords	
Short	Long	Short	Long
nuu	askura	app	paltenpes
mäy	hanekus	spöl	untufes
loo	ihunna	risp	mastuplin
ruo	lokusa	stry	hirramit
hii	olunti	tirk	gurrafrud
pei	pikolis	prul	flusdinnel
reu	solanu	svick	dyskafus
äi	tinnulo	fipp	firrstypa

2.5: Examples (English translations) of test sentences for the eye tracking study in Experiment 5

(1) The man owned 3 houses and 2 luxury cars.

(2) We ordered 2 coffees and 4 doughnuts for breakfast.

(3) The number 1 bus goes every 8 minutes.

(4) During the summer I spent 9 days in France and 5 days in Spain.

(5) I need to write 2 essays and read 5 books in order to pass the course.

(6) I was so hungry that I ate 2 hamburgers and 5 portions of French fries.

(7) I woke up at 8 o'clock and took the number 7 bus to school.

(8) Leo has 4 brothers and 1 sister named Mia.

2.6: Digit words, International Phonetic Alphabet (IPA) transcriptions, and number of syllables for digits (1-9) in Spanish used in Experiments 6, 7, & 8.

Digit	Digit word	IPA	Syllables
1	uno	'uno	2
2	dos	dos	1
3	tres	tres	1
4	cuatro	'kwatro	2
5	cinco	'θinko	2
6	seis	seis	1
7	siete	'sjete	2
8	ocho	'otʃo	2
9	nueve	'nweße	2

2.7: Digit words, International Phonetic Alphabet (IPA) transcriptions, and number of syllables for digits (1-9) in Greek used in Experiment 9.

Digit	Digit word	IPA	Syllables
1	ενα	'ena	2
2	δυο	'δeeo	2
3	τρια	'treea	2
4	τεσσερα	'tessara	3
5	πεντε	'pente	2
6	εξι	'eksee	2
7	επτα	ef'ta	2
8	οκτω	oh'to	2
9	εννεα	en'nea	3

2.8: Short and long words in Spanish (and English equivalents) and English, frequency counts per million (Juilland & Chang-Rodriguez, 1964; Kucera & Francis, 1971 respectively) in Experiment 10.

	Word length					
Language	Short			Long		
Spanish						
	vaso	328	glass	problema	346	problem
	arbol	148	tree	sentido	314	sense
	fuego	132	fire	imagen	244	image
	noche	540	night	minuto	160	minute
	hija	336	daughter	muchacha	138	youth
	carta	206	letter	semana	122	week
Mean		282			221	
English	table	198		government	417	
	water	442		example	292	
	woman	224		century	207	
	money	265		evidence	204	
	city	393		beginning	164	
	picture	162		performance	122	
Mean		281			234	

2.9: Short and long words in Spanish (and English equivalents) and English, frequency counts per million (Juilland & Chang-Rodriguez, 1964; Kucera & Francis, 1971 respectively) in Experiment 11.

	Word length					
Language	Short			Long		
Spanish						
	hebra	12	thread	pestaña	10	eyelash
	vega	10	plain	gigante	10	giant
	mantón	12	shawl	estuche	12	case
	cerco	12	hoop	gusano	10	worm
	horno	12	oven	folleto	10	pamphlet
	naipe	12	card	sábana	12	sheet
Mean		11.7			10.7	
English	elbow	10		physician	14	
	walnut	11		container	10	
	puzzle	10		nursery	13	
	ribbon	12		pineapple	9	
	harvest	12		tablespoon	6	
	pepper	10		reservoir	10	
Mean		10.8			10.3	