Mechanisms of Cognitive Reserve: Computational and Experimental Explorations

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Abstract

Cognitive reserve is the name given to the latent variable that describes individual differences in the ability to offset cognitive decline in old age. This thesis attempts to provide mechanistic explanations for two major aspects of cognitive reserve. These are neural compensation and neural reserve. Furthermore, behavioural experiments carried out as part of this investigation have extended the knowledge of existing theories as to the age invariance of neural compensation and the relationship between language, other more traditional proxies of cognitive reserve, and executive control. The results of these studies carried out in this thesis have demonstrated a biologically viable mechanism for the monitoring of task demand with resultant control of interhemispheric communication as a method of compensation. Further, this aspect of neural compensation was not found in younger participants. The neural network model in this thesis demonstrated differences over age in the spacing of representations for bilingual and monolingual networks as well as demonstrating increased inhibition in the bilingual network as a result of a negative relationship between weights from the tags of each language to nodes in the hidden layer. Finally, regression analysis using data from two large scale behavioural experiments demonstrated a minimal influence of bilingual language use on performance in executive control tasks. The models in this thesis provide an insight into the mechanisms behind cognitive reserve whilst supporting empirical results. Further, the results from the neural network model allowed predictions to be made with regard to the performance of bilinguals in dual category retrieval tasks. The lack of a relationship between bilingualism and cognitive control is supported by emerging research in the area and suggests that the functionality underlying cognitive reserve may be better described by biological rather than cognitive processes.

Declaration

I declare that the work presented in this thesis is my own. When it builds on other peoples' work or ideas, this is clearly marked.

Nicholas Robert Rendell

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Chapter One: Cognitive Reserve

1.1 Introduction

This chapter describes the theory of Cognitive Reserve (CR; Stern, 2003) and the neurobiological events associated with it. This introduction will briefly introduce these sub-concepts and then follow with an overview of what is meant by reserve with clarification of the term compensation. Prior to introducing the main concepts, a discussion of the variability in cognitive ageing will be provided. The concept of Brain Reserve (BR; Katzman, 1993; Stern, 2009), a quantitative view of offsetting age-related decline, will then be described. Following this, Cognitive Reserve (CR; Scarmeas & Stern, 2010; Steffener & Stern, 2012; Stern, 2009) will be described as the overarching theme to the two separate concepts of neural reserve and neural compensation investigated in this thesis. Also included in this chapter is a review of the biological and cognitive factors associated with ageing.

1.2 Variability in decline

Given the biological implications of ageing, many of which are described later in this chapter, it is easy to think that human beings are doomed to an existence of slow decline towards cognitive dysfunction. However, variation within the population of older adults in terms of their cognitive performance suggests that factors exist which can mitigate this biological decline. For example, in a study involving approximately 1500 adults from the Betula cohort (described in Nilsson et al., 2004), a Q-mode technique was applied to the results from the results of 23 cognitive tests, including free recall, cued recall, recognition tasks, and the MMSE in order to classify those individuals with regards to their success in cognitive ageing (Habib, Nyberg, & Nilsson, 2007; Figure 1.1) The Q-mode technique differs from traditional principal component analysis or factor analysis in that it offers a better technique for judging the similarity between cases. This is due to the fact that rather than clustering variables on a set of cases, as in R-mode factor analysis, Q-mode analysis clusters the cases (Reyment & Jvreskog, 1996).

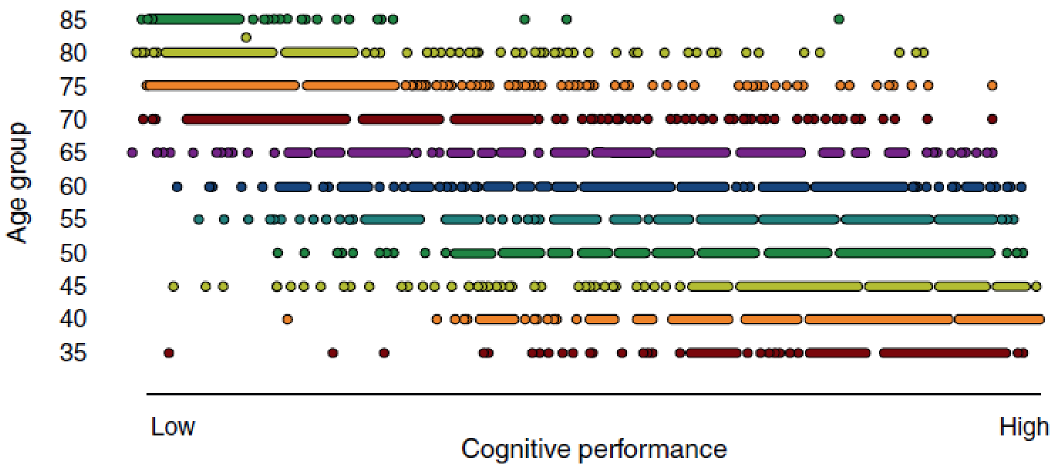

Figure 1.1: The results of Q-mode factor analysis on the results from performance on 23 cognitive tasks by individuals from the Betula longitudinal study. Different colours differentiate age bands. Each single point on the graph represents the mean score of the in individual. Taken from Nyberg et al. (2012).

Of those who were tested, approximately 10% of those over 70 were considered to have aged successfully. In this case, the definition of successful ageing has been adapted for behavioural measures from a physiological definition (Rowe & Kahn, 1987) and can be described as very little or no decline in cognitive function in comparison to the average performance of their younger counterparts. This related to approximately 10% of participants older than 70 years. What this study demonstrates is that cognitive decline in ageing is not a forgone conclusion. However, what remains to be seen is why some individuals maintain a high level of cognitive functioning. The following sections describe theories which provide different perspectives on the way in which biological and environmental factors describe this variability in the population. Before this occurs, clarification of two terms used with regard to these theories is provided.

1.3 Compensation and Reserve

When described in relation to the human brain, reserve is the ability of the withstand insult from stroke, pathology or simply the biological decline associated with normal healthy ageing. Stern (2002) presents reserve as having two subdivisions, passive and active. Passive models of reserve relate to the amount of damage that an individual can sustain before clinical manifestation. The active view of reserve relates to changes in the way that task is processed in order to offset any decline experienced. Stern also states that these two subdivisions are not mutually exclusive but for the purposes of clarity, these perspectives and their accompanying theories are defined separately.

Used on its own, the term compensation has a number of definitions and has been used in a variety of ways in psychological literature. The definition of compensation, for the purposes of this thesis, is the covering of the mitigation of losses or deficits through any number of identifiable mechanisms (Backman & Dixon, 1992). Compensation, according to Stern (2009) is the term applied when there is a difference in cognitive functioning between two individuals suffering the same type and level of neural disruption. This may be due brain damage or disease pathology e.g. Alzheimer’s disease. The difference will be due to individual differences in the level of reserve and would result in differing levels of performance outcome, from low levels, barely maintaining a degree of function through to normal functioning. Therefore, as the brain experiences a loss of resources at a physical level, loss of function at a computational level inevitably follows. What changes from individual to individual is the ability to compensate for this loss.

1.3.1 Brain Reserve

Brain Reserve (BR) stems from an initial theory (Katzman, 1993; Terry et al., 1991) which represents a quantitative view of protection against neurological insult due to the amount of substrate that an individual has available. For example, Roth (1986) observed a requirement for a decline on average in 85% of dopaminergic cells in the striatum prior to the manifestation of clinical Parkinson's disease. With regards to vascular dementia, it was observed that a critical threshold of between 50-100 cc in volume for the clinical manifestations of dementia to occur (Tomlinson, Blessed, & Roth, 1970). This quantitative approach to dementia was also applied to the observation that an increase of on average more than 60% frequency of neurofibrillary tangles and senile plaques observed in an individual resulted in a clinical manifestation of Alzheimer's disease. Individual differences in these quantitative measures is known as Brain Reserve Capacity (BRC; Satz, 1993). This lends itself to a model in which differing BRC leads to variation in the amount of decline occurring prior to clinical expression. This is known as the threshold model (Figure 1.2).

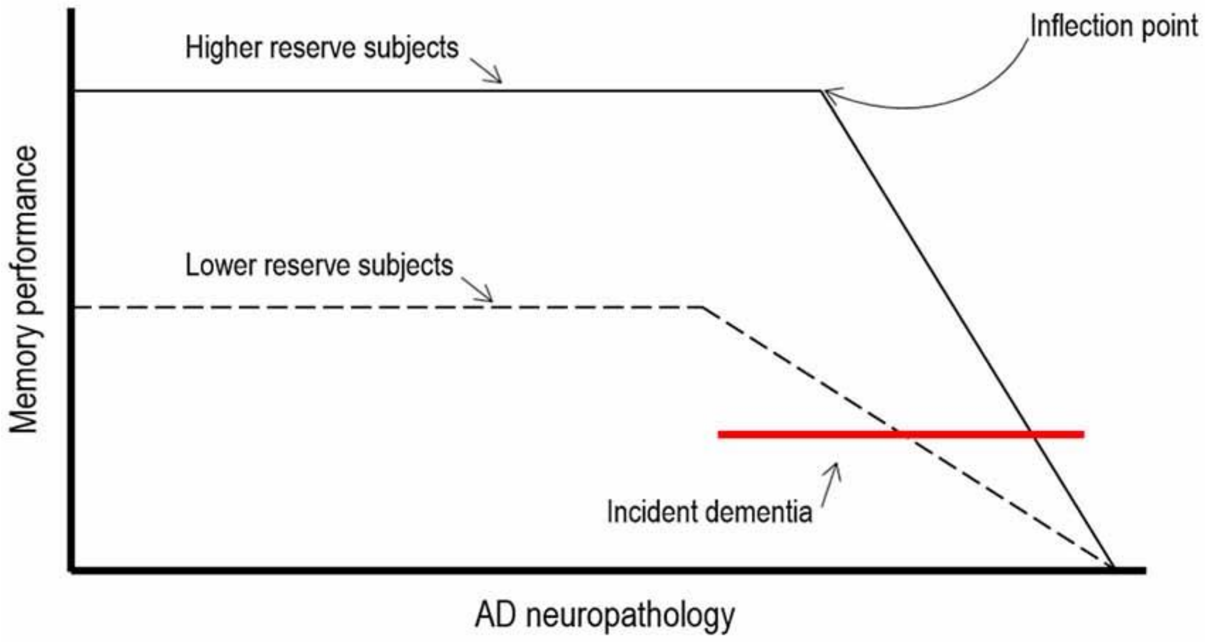

Figure 1.2: Graph representing the threshold model (Satz, 1993). Larger amounts of brain reserve mean a longer time period with dementia pathology prior to its manifestation at the behavioural level. Note that according to this model, both high and low brain reserve subjects ultimately experience performance collapse at the same resource level.

In upgrading the concept of BR, Stern (2003, 2009) presents a passive view of compensation in which reserve represents additional biological resources over and above those necessary to carry out day-to-day functioning. The amount of decline in an individual is the function of a quantitative measure of brain substrate such as brain size or synapse count and the extent of the disease pathology or damage. However, whilst both decline and the means to mitigate such decline sit firmly at the biological or hardware level, the manifestation of this interplay is most important at the cognitive or algorithmic level.

The concept of BR differing between individuals has been demonstrated in healthy older individuals (50 to 81 years) as a positive relationship between head size, speed of processing and global cognitive functioning (Tisserand, Bosma, Van Boxtel, & Jolles, 2001). This relationship endured when explicit adjustment was made for age, sex, and education level. An investigation of the association between head circumference and AD was carried out with a logistical regression analysis (Schofield, Logroscino, Andrews, Albert, & Stern, 1997). Controlling for ethnicity, gender, education, age, and height with AD as the outcome of interest, the analysis demonstrated that women whose head circumference was within the lowest quintile had approximately 2.9 times greater likelihood of AD. Furthermore, men in the same quintile had the slightly lower risk of being 2.3 times more likely to have AD. However, the results of this study demonstrate that the risk factors are only present for those individuals with the smallest head circumference.

Whilst providing some evidence of a relationship between a quantitative measure of brain substrate and protection against age-related neurological decline, more refined measures are needed, such as those provided by imaging studies. For example, a MRI based study carried out by Mori et al. (1997) gave a more accurate estimation of the current volume of biological substrate in a sample of 60 patients with probable AD than head circumference. Further, the authors were able to calculate a statistically valid estimation of the patient’s premorbid brain volumes, calculated from intracranial volume. Given these values, the authors found a positive relationship between premorbid brain volume and cognitive functioning in terms of scores on the WAIS-R and the Raven Coloured Progressive Matrices (Raven, 1958). These results demonstrate that that larger amounts of brain substrate lead to a greater cognitive buffer against age-related dementia pathology. More recent imaging techniques have allowed the biological measures to become more nuanced and associations between such measures as dendritic spine length and dendritic density can be expected (Lövdén, Wenger, Mårtensson, Lindenberger, & Bäckman, 2013).

In brief terms, these findings suggest that those individuals with a greater amount of grey matter have a greater buffer against neurological decline. However, to be able to generalise to a wider population, the starting assumption must be that all individuals have roughly the same quantitative tolerance to neurological insult or decline with regards to cognitive performance. Further, no clear relationship exists between the changes at the biological level and cognitive decline (Stern, 2009). For example, from a sample of 678 catholic nuns who were found to have neuropathological markers of Alzheimer’s Disease (AD), only some of them demonstrated cognitive deficit when alive (Snowdon, 2003). Furthermore, Katzman at al.(1989) describes ten cases of cognitively intact elderly females whom, upon post mortem, were discovered to possess the neurophysiological markers of advanced Alzheimer’s disease (AD). Therefore, whilst a relationship between the biological and the cognitive must surely exist, an explanation is required to be able to describe the modulatory variable that exists between both levels of description.

1.3.2 Cognitive Reserve

Whilst BR represents a passive form of offsetting neurological decline, the theory of Cognitive Reserve (CR) represents an active view (Stern, 2002, 2003, 2009). Whereas BR is exclusively explained on the hardware level, CR stands as a bridge between the biological and cognitive domains. Within this concept, two main themes arise, neural compensation, and neural reserve. Neural compensation is defined as the recruitment of neural substrate for processing a particular function with which it is not normally involved (Barulli & Stern, 2013). Neural reserve, on the other hand, can be defined as the strengthening of existing pathways and focuses more on the activity of biological neural networks in the enlistment of pre-existing cognitive programmes and compensatory strategies (Hindle, Martyr, & Clare, 2014). Neural compensation is explored in Chapters two and three whilst neural reserve is explored in Chapters four and five. In this section, the principle of CR as a whole is discussed. A summary of the main concepts and theories is provided in Table 1.1.

Unlike BR, which can be described in quantitative measures such as brain size or synaptic counts, CR is measured in terms of proxies. These proxies are specific environmental measures, such as years of education, which positively correlate with the ability to offset cognitive decline. These conceptually underlie the sub-concept of neural reserve since greater practice or exposure of particular cognitive functions may strengthen them against later decline (Barulli & Stern, 2013). Mortimer, Snowdon, & Markesbery (2003) investigated the relationship between markers for Alzheimer's Disease (AD), a diagnosis of probable dementia, and head circumference in a sub sample of the Catholic nuns described previously (Snowdon, 2003). Whilst head circumference was very clearly a measure of BR, a measure of educational attainment was also taken, with less than sixteen years relating to low educational attainment and more than sixteen years relating to high educational attainment. With both age and the presence of biological markers of AD controlled for, the results demonstrated a significant negative correlation between educational attainment and incidence of dementia. Furthermore, an interaction between head circumference and educational attainment was also found with those individuals with a smaller head circumference and low educational attainment being at greatest risk for AD. The association between educational attainment and risk of dementia demonstrates the influence of environmental factors as a measure of cognitive reserve. Other proxies which have demonstrated a relationship with the offset of cognitive decline include leisure activities (Scarmeas & Stern, 2003) and occupational attainment (Garibotto et al., 2008).

Another example of how CR may manifest itself is through the observed changes in brain activation over age. This is also evidence for the sub-concept of CR, neural compensation in which alternative brain networks are responsible for the accrued reserve. Once specific way in which this is observed is through the shift in the pattern of activation intrahemispherically from the occipitotemporal lobe to the frontal cortex. This is known as the posterior to anterior shift in ageing (PASA; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). The pattern was initially reported by Grady (1994) in a study demonstrating weaker activity in the occipitotemporal region together with a reduced dissociation between the dorsal and ventral streams. Importantly, the drop in activation in the occipital lobe was associated with stronger activation in the prefrontal cortex. The additional activation in frontal regions has been interpreted as the elaboration of perceptual processing as compensation for less efficient processing by the visual cortices (Davis et al., 2008; Spreng, Wojtowicz, & Grady, 2010). Another model of neural compensation is the hemispheric asymmetry reduction in older adults HAROLD observation (Cabeza, 2002). This is introduced at end of this chapter as the mechanisms behind this observation are explore in this thesis.

Whilst CR may vary between individuals and would therefore explain the differences in performance between groups of older adults (Reuter-Lorenz et al., 1999; Cabeza et al., 2002) how this is underpinned by the biological substrate is unclear. Stern (2002a; 2003) cites differences in resources such as synapses as a biological explanation for CR. However, the mechanisms behind both neural reserve and neural compensation are unknown. Stern describes more efficient individuals as ‘calling up’ alternative brain networks. Since no qualification as to what calling up means, this statement highlights the lack of understanding of the biological substrate sub serving the offset of decline.

Generally, CR manifests itself as a difference between individuals who are experiencing neurological decline through healthy ageing or disease pathology. However, studies have also demonstrated differences in performance between younger adults in relation to scores on proxies of CR. For example, Stern et al. (2005) used a non-verbal task in which healthy younger and older participants were required to make a decision as to whether a series of highlighted probes were new or old in response to a series of the same size of unnameable shapes. The participants undertook the tasks whilst being imaged using positron emission tomography (PET). The number of shapes that the participant had to encode determined task demand with two conditions, the harder of which was titrated to achieve 75% accuracy in participants. CR for the participants was assessed by years of education and IQ measured by New Adult Reading Test (NART) and the Wechsler Adult Intelligence Scale-Revised (WAIS-R). The results demonstrated a higher activation pattern for participants with lower CR with less activation correlating with better performance ($r = -.5$, $p<.05$). The study described above represents a difference between individuals that is related to proxies of CR.

1.4 Summary of the main concepts explored in this thesis.

Table 1.1: Table summarising the main concepts explored in this thesis.

Brain Reserve (BR)	A passive view of reserve which encompasses biological proxies as a buffer against neurological decline. Differences in BR are manifest in an individuals' brain reserve capacity (BRC; Satz, 1993)
Cognitive Reserve (CR)	An active view of reserve which describes the ability to cope with neurological decline at the cognitive level. This is due to variability in the efficiency of utilisation of neural circuits (Stern, 2002). Theoretically, BR can be held constant but changes in CR will cause behavioural variability.
Neural Compensation	A sub-category of CR in which reserve is provided by alternative brain networks to those normally ascribed to a particular task (Tucker & Stern, 2011).
Neural Reserve	Great efficiency in a particular cognitive network ascribed to a particular task as a result of increased exposure (Barulli & Stern, 2013).

1.5 Levels of description

Although different in the sense of how active they are perceived to be, both BR and CR may also be viewed as the same system but described on different levels. Throughout this thesis, different levels of explanation are relied upon. Therefore, not only must the theories be situated on the level upon which they are described but also on the scale at which they take place. With this in mind, levels of description will be discussed.

As with most complex systems, the study of the brain can be undertaken on a number of levels, all of which need only be causally related. For example, the topological description of the site of damage for a stroke victim would differ in its level of description to any cognitive deficits that may occur as a result of this damage.

To understand a complex system fully, description can be carried out on three levels. Zenon Pylyshyn (1984) defined them as the *semantic* the *syntactic* and the *physical*. David Marr (Marr & Poggio, 1977; Marr, 1982b) provided the seminal description of these three levels, the computational, the algorithmic and the implementational; all of which are described in this section. The first level, the computational, provides a detailed description of the mapping of one property to another as well as providing a description of *what* is being computed. However, what is being manipulated can be represented in a number of ways. Using Marrs' original example of a cash register, a description at the computational level would be the mathematics being carried out by the register with the tokens being manipulated represented in a number of ways, such as Arabic, binary or Roman. This leaves the rest of the explanation at the computational level as to *why* the process is computed. This might be the question as to why addition is used when working out the price of goods rather than multiplication. The *algorithmic* layer is the middle layer and describes how the transformation from input to output may occur. As with the representations manipulated within the system, there may be a number of methods of transformation, as Marr states; '…the algorithm often depends rather critically on the particular representation that is employed' (Marr, 1982, page 23). The final layer, the *implementation* or *hardware*, defines the physical substrate within which the representation and algorithm can be realised. In the case of the mind, the substrate is the brain at a neural level. Later in this thesis, the biological plausibility of connectionist networks will be explored. Additionally, an outline of the discussion as to where connectionist models reside in Marrs' three levels will also be included.

Cognitive reserve differs from the BR model in that CR reflects the ability for an individual to exhibit greater robustness to damage because they carry out cognitive processes in a more efficient manner or have the flexibility to utilise different neural networks for alternative tasks in the event of age related or pathology related neurological decline. This suggests a link between BR, residing on the implementational level and CR which sits astride the implementational and the algorithmic level of description. As such, CR manifests itself in the individual differences in the moderation of the relationship between neurological decline and cognitive performance. For example, observations of higher brain activation in relation to lower proxies of CR (Stern et al., 2005) may reflect a less efficient neural system at the implementation level and/or different but equally unsuccessful cognitive strategies at the algorithmic level. Both of these may be variable throughout the population.

1.6 Bilingualism

In addition to proxies such as level of education and lifestyle factors, a number of studies have demonstrated that the use of a second language relates to how long it is before an individual demonstrates the behavioural symptoms of dementia. For example, Bialystok, Craik, and Freedman (2007) carried out a study in which 184 patients were selected from a set of 228 patients with a diagnosis of probable or possible Alzheimers disease (AD) who had been referred to a memory clinic complaining of poor cognitive function. Of the selected patients, 51% were judged to be bilingual with approximately 90% of those being immigrants. One of the initial findings was that on average the bilingual participants were 3.2 years older than the monolinguals when they presented themselves to the clinic with cognitive dysfunction. Further analysis investigated the interval between the initial onset of symptoms and the first visit to the clinic to counter the notion that bilinguals (or migrants) might take longer to seek help. When this was taken into account, bilinguals demonstrated a delay of over four years in the onset of symptoms. Given the association between years of education and cognitive reserve (Albert et al., 1995; Barnes, Tager, Satariano, & Yaffe, 2004; Scarmeas, Albert, Manly, & Stern, 2006) and the potential relationship between educational attainment and acquiring a second language, educational status was included as a covariate in an additional analysis. This did not reduce the overall effect of bilingualism in delaying the onset of Alzheimer’s disease. Further, the authors found no difference in years of formal education between both groups.

Chapter Four investigates the contribution of bilingualism to CR by presenting a neural network model of bilingualism. The study is based on the proposal that inhibition of both lexical and categorical representations is greater in bilinguals due to greater overlap in the representational space. This is evidenced by errors and prolonged reaction time during for bilinguals during recall (Gollan & Acenas, 2004; Gollan et al., 2002) as well as categorical interference (Kroll, 2009). This inhibitory practice over age is ultimately responsible for some aspect of cognitive reserve. As well as taking closer spacing between representations as requirement for increased inhibition, the study also investigated inhibition within the network by examining the relationship between features of the input set of the network and their influence on the hidden layer.

1.7 Cognitive Reserve, MCI and AD

This section describes the transition from normal healthy ageing to the diagnosis of AD and discusses the evidence for CR in this context. CR becomes more pertinent when the slow decline associated with normal healthy ageing develops into mild cognitive impairment (MCI), a state from which Alzheimer’s disease (AD) is more likely (Zhao et al., 2007). The supposition is that a continuum of decline exists from one to the other. However, research demonstrates that this is far from linear (Samtani, Raghavan, Novak, Nandy, & Narayan, 2014). This indicates a level of cognitive function that is slightly lower than would be expected from an individual of that age without manifesting the symptomology of Alzheimer’s disease. Conversion from individuals with MCI to clinically probable Alzheimer’s disease is approximately 10-15% per annum (Petersen, 2000). However, not all individuals with MCI go on to develop Alzheimer’s disease (Petersen et al., 1999). In terms of cognitive function in those groups with MCI, the difference in performance between this group and controls is limited to memory. However, significant differences remain within this domain. A study by Peterson et al (1999) presented a number of measures of cognitive function to groups of individuals with MCI and varying stages of Alzheimer’s disease. Participants with MCI performed worse than healthy controls on presentations of the Wechsler Memory Scale (revised; WMS-R) in both logical memory and visual reproductions.

Typically, cognitive decline associated with MCI appears about three to four years before the clinical conditions for Alzheimer’s are met (Small, Fratiglioni, Viitanen, Winblad, & Backman, 2000). As cognitive impairment progresses, the patient reaches a point at which a diagnosis of probable AD is possible. From a cognitive perspective, for a diagnosis of Alzheimer's to be made, a number of deficits must be present. Primarily, memory impairment must be displayed with either aphasia, apraxia, agnosia or decline in executive function also present (American Psychiatric Association, 2000). From this, a diagnosis of probable Alzheimer's can be made. Definite diagnosis of Alzheimer's is made when biological markers are present (Dubois et al., 2007). However, the rate at which decline occurs appears to be quadratic. Patients with mild and late Alzheimer's disease demonstrate a slower rate of decline than those with moderate dementia (Stern et al., 1994). Further, the performances of late stage Alzheimer's patients may be confounded by floor effects created by communication difficulties.

Unlike healthy individuals for whom high levels of CR are associated with generally larger global brain measures, higher levels of CR in patients presented with AD or MCI is associated with how far the biological markers associated with the MCI-AD continuum have progressed. This is due to the relationship between CR, the biological pathology of AD and the level of cognitive dysfunction at which the symptoms manifest themselves. If behavioural symptoms are equated for, those with greater CR have more severe pathology. Conversely, if severity of pathology is equated for, those with greater CR will have milder symptoms. In simplistic terms, individuals with the higher level of CR had greatest ability to withstand the biological onslaught of the disease before manifesting behavioural deficits. Therefore, much in the same way as BRC, CR in terms of neural reserve, fits the threshold model described previously (see figure 1.2.).

1.8 Biological underpinnings of cognitive reserve

Whilst the specific mechanisms behind cognitive reserve are unknown, some general properties of the brain give an indication as to how they can be implemented. Firstly, for the brain to adjust over time it needs to be plastic. It is reasonably well established that neurogenesis, the creation of new neurons, declines as we get older (Molofsky et al., 2006). Therefore, it is of greater importance that there is the ability to create new connections between neurons and brain regions to contribute to the mitigation of this effect. Furthermore, compensation is more effective if the brain regions from which recruitment occurs is healthier than that which is doing the recruiting.

1.8.1 Synaptogenesis

The ability for neurons in the central nervous system to create or strengthen new synapses with other neurons (synaptogenesis) decreases over age but this is not to say that it completely disappears. Whilst the possibility of neurogenesis appears to be increasingly less likely as senescence progresses, synaptogenesis, the development of new synapses seems a possible if not delayed process in ageing adults (Churchill et al., 2002; Kevin, 1986). Animal research by Hof et al (1981) and Kevin (1986) demonstrates the ability to grow new connections in rats can continue into senescence. Evidence has been found that glial cells have a large role to play in the production of new synapses. Although an indirect link exists between the two as increased support provided by glial cells will provide the resources for increased growth, the results from studies of cells in culture demonstrate that synaptogenesis may be mediated by glial cells in more direct ways (Slezak & Pfrieger, 2003). Even if running at a reduced rate, the ability to develop new connections within certain brain areas presents the opportunity for compensation, especially if new connections are formed between areas of low and high resources.

1.8.2 Pathoclysis

As brain ageing is not a holistic, uniform phenomenon, it follows that some areas of the brain atrophy at slower rates and therefore provide the resources for those regions that have declined at a faster rate. Different brain regions age at different rates, known as *pathoclysis* (Raz, Torres, Spencer, & Acker, 1993). For example, imaging-based research carried out by Raz et al (2003) demonstrates differing age-related atrophy in localised prefrontal areas in comparison to the primary somatosensory cortex suggesting that a different rate of ageing occurs among regions. This pattern is reflected in a number of studies which demonstrate that in relation to global grey matter loss, the loss associated with the frontal cortices and temporal lobes is typically accelerated (for a review see : Kemper et al., 1994). These studies show that biological resources that are less damaged than other areas are available to provide additional processing power.

1.9 Cross-sectional and longitudinal studies

Studies investigating CR fall into two broad categories. Firstly, cross-sectional studies investigate the cognitive intactness of a number of individuals in relation to their level of CR. For example, Solé-Padullés et al. (2009) investigated 16 healthy cognitively intact participants, 12 with MCI and 16 with AD for any relationship between proxies of CR and cerebral measures. In this case, proxies of CR included IQ and a measure of the level of intellectual and social activities engaged in by the individual. In the healthy cognitively-intact individuals, higher scores in relation to these proxies was related to larger brains and a reduction in brain activity during MRI scanning whilst carrying out a vision encoding task. However, in those individuals with MCI and AD, higher measures of the proxies of CR were associated with reduced brain volumes. Furthermore, at least in the group with AD, greater activation was observed, both in the right superior temporal gyrus and in the left superior parietal lobe.

Following a group of individuals over a protracted time period means that the relationship between pre morbid levels of CR and the risk of developing Alzheimer's disease can be investigated. This is the model that a number of longitudinal studies of CR have taken. For example, Stern et al (1994) found a relationship between incidence of AD and educational experience. They identified 593 individuals aged 60 and above who did not demonstrate any dementia pathology. Each participant was scored for both educational and occupational attainment. Four years later, of the 593, 106 acquired dementia with an increased risk for those participants who had scored low on either educational or occupational attainment. The results from this study suggest that higher achievers have greater amount of CR and are therefore able to delay the behavioural effects of dementia. Further, Ott et al. (1999) followed 6827 non-demented individuals for an average of 2.1 years. From the 137 new cases of dementia within that sample, it appeared that that the group that demonstrated the greatest risk were females with a lower level of education. For differing levels of description, these results require differing explanations. On an implementational level, larger brains may lead to better educational circumstances which in turn provide the CR. Furthermore, education appears to provide the cognitive faculties to turn to alternative strategies. These statements leave open the possibility that a larger brain may be directly responsible without education. Whilst all higher level operations must ultimately answer to their biological substrate, additional training may only be a modifier rather than the basis of reserve.

The issue with cross-sectional studies are twofold and each of these criticisms targets a different level of description. Firstly, at the algorithmic level, the question arises as to whether or not the participation in education or stimulating activities leads to an individual being more cognitively capable or vice versa (Scarmeas & Stern, 2003). Furthermore, from the perspective of hardware level and the biological markers of dementia pathology, it is difficult to understand the exact point at which an individual is in terms of the progression of their disorder. Combining these two issues, the trajectory of performance versus age can change at any point in an individual's lifespan due to the interaction of any number of contributory factors. Therefore, even studies which do have some temporal depth may not give the greatest indication of where an individual is likely to be at any point in the future or give any clear indication of what happened between the current and previous time of testing. Evidence from the neural network model of bilingualism in chapter four demonstrates the variation in performance trajectories between individuals due to a limited number of age and reserve related factors.

1.10 Connectionist study of cognitive reserve

Chapter Four provides a connectionist perspective of the development of cognitive research through the use of bilingualism. The motivation behind specifically using a connectionist model for this investigation is that they represent the same sort of constraints that might be found in the neural processing of language. Furthermore, these similarities allow a level of description which can bridge the gap between activation observed on the neural level and cognitive processes. Connectionist models of bilingualism come in two distinct flavours which are related to their architectures. These are either localist or distributed architectures. Localist models usually involve a more symbolic level of processing and the network is divided into units corresponding to words and letters or features of a particular letter and do not incorporate change according to experience into their design. As such, their utilisation is normally related to investigation at a particular point in time rather than a developmental perspective (Thomas & van Heuven, 2005). Given the longitudinal nature of the current study, an in-depth description of localist networks will not be included but some description will be given of relevant models. For a comprehensive review of the differences between distributed and localist models and the advantages and disadvantages of each, see Seidenberg (1993).

This study uses artificial neural networks or distributed connectionist networks. This sets them on a different level of description (Marr et al., 1977; Marr, 1982b) to their localist counterparts and classical models of cognition (Broadbent, 1985; McClelland & Rumelhart, 1985). This is due to the lack of symbolic meaning associated with the individual computational elements or *nodes* when compared with classical models of cognition. Although the presence of rules in a symbolic model of cognition presents the ability to explain function it does not mean that these processes themselves are actually implemented in any way within the human brain. Connectionist modelling can offer an *implementational* description of cognitive processes (Sejnowski, Koch, & Churchland, 1988) by carrying out computation in a parallel manner akin to the human brain. A full description of connectionist networks will be provided in the introduction to Chapter Four.

1.11 Ageing

For the concept of CR to be properly explored, some description with regards to the decline for which it offsets, is necessary. This section will begin by describing the biological factors common to the ageing brain as well as some of the risk factors associated with but not necessarily exclusive to ageing. Following this the cognitive effects of age are described. It is the poor relationship between the biological and the cognitive which underpin the theory of CR.

1.11.1 Biological ageing

Physically, the difference is obvious. To hear a colleague complain about their knees or back is commonplace. What is not so obvious, at least initially, is that ageing affects the human nervous system just as it affects the rest of the body (Park, Polk, Mikels, Taylor, & Marshuetz, 2001; Raz, 2004; Raz, Craik, & Salthouse, 2000). Changes in the brain initially occur at a microscopic level and then manifest themselves at the gross morphological level. These biological changes, subsequently impact the level of cognitive function (Stern, 2003).

The size of the brain changes during ageing, a primary indication that ageing effects the central nervous system. Previous to the proliferation of imageing studies, post mortem studies gave the peak brain size during life span as during the third decade (Kemper et al., 1994). After this peak, the average overall decline in brain weight over the remainder of lifespan is 92g for males and 94g for females (Dekaban, 1978). As well as overall weight, the volume of the brain also decreases. Miller, Alston, & Corsellis (1980) looked at brain volumes rather than weight and found that these also decreased. This occurred from around age 50 from which an average of 2% per decade was observed for both sexes.

Four decades of imageing have provided a well-replicated and in-depth picture of brain volume in vivo. In terms of gross morphology, enlargement of the ventricles is a clear indication of a reduction in grey matter volume. Berardi, Haxby, De Carli, & Schapiro (1997) examined ten healthy young and ten healthy older adults using computed tomography (CT) and found significantly larger lateral ventricles in older subjects. Enlarging of the ventricles (ventriculomegaly) starts at a young age and occurs at the rate of approximately 3% every year and accelerates as ageing progresses (Raz, 2004). Investigation using CT scan reported volumetric increases in size of the lateral and third ventricles as well as a volumetric loss of grey matter, both of which correlated with age (Schwartz et al., 1985).

Study of the external structure of the neuron and neural networks has revealed a change in the connectivity of the neural network (Kemper, 1994). These reductions in connectivity may explain the alterations observed at a gross morphological level rather than large-scale cell death (Raz, 2004). In combination with a number of researchers, Dorothy Flood has carried out a number of studies using Golgi-Cox techniques and observed reduction or stabilisation of dendritic growth within areas of the hippocampus (Flood, 2005; Flood, Buell, DeFiore, Horwitz, & Coleman, 1985; Flood, Buell, Horwitz, & Coleman, 1987; Flood, Guarnaccia, & Coleman, 1987a, 1987b; Hanks & Flood, 1991). It is suggested that these changes may be due to the breakdown of intercellular processes described below. This is especially true considering the disruption of protein synthesis due to inefficient DNA repair (Lu et al., 2004). The age-related changes and associated risk factors which lead to morphological change are described below.

1.11.2 Vascular ageing

As the brain ages, a number of phenomena occur within the CNS at a microscopic level. Morphologically, the nature of the arteries, arterioles and venules changes with age. The vascular system of the brain is straight and organised in younger adults but becomes '…coiled, tortuous and differentially dispersed' (Ivy, MacLeod, Petit, & Markus, 1992; p.284) during senescence. Ivy et al discuss the consequences of vascular reorganisation, suggesting that changes to the structure of the vascular system have a detrimental effect on the permeability of the blood brain barrier. It is these changes in the morphology of the vascular system that may account for the observed reduction in cerebral blood flow (Farkas & Luiten, 2001). It is not yet known whether changes in cerebral vasculature precede the structural and intercellular changes that are described within or vice versa (Churchill et al., 2002). However, what is clear is that a dynamic exists between both phenomena regardless of the order of occurrence. Further, the vascular changes that occur during ageing contribute to the deleterious impact at a computational level since it has been demonstrated that a mild but constant reduction in overall levels of oxygen levels in the brain have been related to poor cognitive performance in animal studies. For example, bilateral ligation of the carotid artery (2VO) in rats produced poor spatial learning and memory performance in a Morris water navigation task and the eight-arm radial maze task (de la Torre et al., 1997; Ohta, Nishikawa, Kimura, Anayama, & Miyamoto, 1997).

1.11.3 Homocysteine

Another contributor to reduced cerebral blood flow is the endogenous amino acid homocysteine. Known to correlate positively with age (Budge, de Jager, Hogervorst, & Smith, 2002), high levels of homocysteine are linked to cardiovascular disease due to the damage it causes to the endothelial cells lining the inside of blood vessels (Bawaskar, Bawaskar, & Bawaskar, 2015; Esteghamati et al., 2014). Relative to cognitive function, elevated levels of homocysteine are also linked with reduced blood flow to the brain (Kumar et al., 2008). As seen with reduced blood flow due to changes in the structure of the venous system of the brain, reduced blood flow also associated with elevated homocysteine levels has been associated with memory impairment (Matté et al., 2009). Further, 55 patients with mild cognitive impairment (MCI) and 44 age-matched, cognitively unimpaired controls were studied to investigate the relationship between cognitive function and homocysteine levels (Siuda et al., 2009). All participants were given a neuropsychological evaluation at baseline and then two more at six monthly intervals. Specifically, participants were provided with the mini mental state examination (MMSE) and the clock drawing test (CDT). Further, episodic memory was assessed using the Rey auditory verbal learning test (RAVLT) and the Rey-Osterrieth complex figure test (ROCFT). Further, they were initially assessed for risk factors such as hypertension, cardiovascular disease, diabetes, cigarette smoking, hyperlipidaemia and elevated levels of homocysteine. The study found that hyperhomocysteinaemia was significantly more prominent in those individuals diagnosed with mild cognitive impairment than the unimpaired control group. From a global volumetric perspective, elevated homocysteine levels have also been associated with reduced brain volume (Seshadri et al., 2008). An indirect relationship with non-specific brain damage has also been associated with homocysteine through its contribution to silent brain infarcts or ‘mini strokes’(Seshadri et al., 2008).

1.11.4 High Density Lipoprotein (HDL)

Another biological factor that contributes to cognitive decline includes the density of High Density Lipoprotein (HDL) in the blood. HDL is a complex particle which transports fat molecules around the body. It is sometimes known as the ‘good cholesterol’ due to the property of transporting fat molecules away from cells including those which belong to the artery walls. In terms of structure, it consists of a number of protein strings and gets its name from its high protein to fat ratio. A lipid profile containing high levels of HDL and lower levels of lower density lipoproteins is associated with lower predisposition to coronary artery disease (Torpy, Burke, & Glass, 2009). This is due to HDLs’ function as a transporter of cholesterol away from the inner lining of the blood vessels (endothelium) to the liver for excretion. Whilst low levels of HDL (dyslipidemia) can be found in individuals with poor diets and lifestyles, HDL can also decline during ageing (Ferrara, Barrett-Connor, & Shan, 1997). An imageing study investigating the association between abnormal levels of lipids and neurodegenerative and neurovascular disease was carried out with 183 participants (mean age 58). Independent of other lipid types, a relationship was found between levels of HDL and grey matter volume. Further, an association was found between levels of HDL in participants and their performance on the Brief Visuospatial Memory Test (Ward et al., 2010). Furthermore, in the oldest old (95 years +), levels of HDL were found to correlate highly with cognitive performance. One hundred and thirty nine participants, each over 95 were given blood tests to ascertain levels of HDL, apolipoprotein A-I and low density lipoprotein (LDL).

Participants were also given the Mini-Mental State Examination (MMSE). The results demonstrated a significant correlation (r = .32, p<.0001) between MMSE scores and HDL levels in plasma. Further, there was a significant difference between participants with higher MMSE scores (25-30) and those with moderate MMSE scores (<25). This difference was found in both males and females although one of the methodological issues with this sample is that females were 2.81 times more prevalent in it (Atzmon et al., 2002). High levels of HDL have also been associated with decreased dementia pathology (Reitz et al., 2010). From 2190 elderly individuals a cohort of 1130 were selected on the basis of having no prevalent signs of dementia following a general health interview, an analysis of medical history neurological examination and a neuropsychological battery. During the 4469 person-years of follow up, 101 cases of Alzheimer's disease were diagnosed. This included 89 clear diagnoses and 12 probable diagnoses. Comparing these individuals to the healthy remainder, it was demonstrated that higher levels of HDL were associated with reduced risk of both probable and possible Alzheimer's disease. Although HDL decreases over age the association with lifestyle factors also suggests a level of variability, the level of which is not totally out of the hands of the individual.

1.11.5 The Ageing Neuron

Lipofuscin, a brownish substance, also known as the 'ageing' pigment, is found in neurons in the cortex and cerebellum (Raz, 2004) as well as other areas in the body. Difficult to remove by the neuron and associated with prion related diseases and Alzheimers, lipofuscin is known to contribute to functional problems in the normal ageing brain (Fonseca, Sheehy, Blackman, Shelton, & Prior, 2005). Fonseca et al (2005) suggest that this is either the result of an inability to metabolise this within the cell or an excess of production. It is understood that the build-up of lipofuscin may interfere with normal intercellular processes resulting in reduced RNA counts (Mann, Yates, & Stamp, 1978). Lipofuscin has been demonstrated to make cells more vulnerable to oxidative-stress, a primary cause of cell death (Sitte, Merker, Grune, & von Zglinicki, 2001; Terman, Abrahamsson, & Brunk, 1999). Intercellular reduction of resources may also be accountable by a decrease in mitochondrial function as well as a reduced ability to repair damaged DNA (T. Lu et al., 2004).

1.11.6 Plaques and Tangles in the healthy ageing adult

Amyloid plaques and Tau neurofibrillary tangles are strongly associated with Alzheimer’s disease (Herrmann & Spires-Jones, 2015). However, both plaques and tangles can occur decades prior to the clinical manifestation of dementia. Using PET scanning techniques, the binding of a particular ligand 2-(1-{6-[(2-[F-18]fluoroethyl)(methyl)amino]-2-naphthyl}ethylidene)malononitrile (FDDNP) to sites of high plaques and tangles concentration demonstrated a high negative correlation with composite cognitive scores for groups of participants with mild cognitive impairment as well as participants who were cognitively intact (Rho = .60, p<.005); Braskie et al., 2010). The same binding molecule was used in a later study which investigated the relationship between concentrations of FDDNP binding and subsections of the profile of mood states questionnaire (Chen et al., 2014). Further, co-varying for age, the results demonstrated that bonding of FDDNP in participants with mild cognitive impairment was inversely associated with scores on the profile of mood states questionnaire (r = -.35, p = .04).

1.11.7 Dopamine

Neurotransmitter decline during ageing has been extensively researched. This is especially true of the monoamines (S.-C. Li, Lindenberger, & Sikström, 2001). It is generally agreed that mesolimbic dopamine (DA) plays a role in memory and learning (Missale, Nash, Robinson, Jaber, & Caron, 1998). Further; pharmacological studies have demonstrated that DA receptors D1 and D2 both play a part in mediating these effects (Levin & Rose, 1995; Sawaguchi & Goldman-Rakic, 1994). Measures of D2 dopamine receptors were gained from a healthy, mixed-sex sample of individuals aged between 19 to 73 years through the use of radioactive ligands binding to these sites and showing up on PET scans (Wong et al., 1984). This provided an in vivo picture of the efficacy of dopamine functionality over age. The results demonstrate a decline in the amount of binding to sites in the caudate nucleus, frontal cortex, and putamen with linear and non-linear decline observed for females and males respectively. The lack of binding sites does not necessarily mean neurotransmitter decline and the decline in cerebral blood flow described above may be an alternative suggestion for these findings. However, post-mortem studies and the activity of synthesising enzymes support a hand-in-hand decline of the neurotransmitters themselves with the available binding sites (McGeer & McGeer, 1976; Severson, Marcusson, Winblad, & Finch, 1982). A more recent PET study has supported the decrease in dopamine over age with a decline in dopamine transporters observed over age. This presynaptic marker of dopaminergic decline was also related to the observed decline of the postsynaptic marker, the D2 receptors (Volkow et al., 1998).

Such a decline in dopamine has been associated with the payment of both cognitive and motor functions. The same general technique of tagging dopamine receptors, in this case D2, in order to quantify dopamine transmission was used with a sample of 30 healthy volunteers with an age range of 24 to 86. The participants also took part in a battery of neuropsychological tests. In terms of D2 receptor availability over age, the results of this study supported the previous research demonstrating decline, in this case in the putamen and caudate nucleus. Further, D2 availability correlated positively with performance decline in a number of tasks with the strongest correlation being with the finger tapping test, a measure of motor performance. Further, correlations were found with a number of cognitive tasks including the Wisconsin card sorting test and the Stroop test. The association with motor performance is hardly surprising given the reduction in dopamine associated with Parkinson's disease (Brandt & Butters, 1986; Lotharius & Brundin, 2002). However, the association between dopamine and cognitive deficits requires explanation.

One theoretical link between the 'correlative triad' of age, dopamine, and cognitive ageing is provided by the neuromodulatory effects of dopamine (Baltes & Lindenberger, 1997). This theory suggests that the decline in the effectiveness of dopamine as a modulator in relatively intact neural circuits such as the dorsal lateral prefrontal cortex (PFC), as well as the effect of decreased receptor availability in these areas, leads to decreased performance in tasks requiring working memory and overall processing speed. The direct association between decreased neuromodulation in the PFC and cognitive decline is due to a related increase in noisiness of representations held within working memory. This occurs through the ability of dopamine to activate GABA neurons and change their temporal firing pattern. This results in a synchronisation of prefrontal oscillatory activity, a property related to the ability to hold perceived features or retrieved representations in working memory (Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006). The overall result is a reduction in the distinctiveness of cortical representations. Evidence for the link between dopamine and cognitive performance has been discussed above, however, animal models have also demonstrated that the introduction of dopamine agonists has reduced working memory deficits in older monkeys (Arnsten, Cai, Murphy, & Goldman-Rakic, 1994). Further, reduced dopaminergic receptor density in the striatum in rats is associated with decreased response speed (MacRae, Spirduso, & Wilcox, 1988). A computational description of the increase in neural noise is provided in chapter four in which dopaminergic decline is incorporated into a model of bilingual language acquisition to simulate ageing.

1.11.8 Hormonal risk factors

The final biological ageing factor considered is that of hormonal risk factors. Hormone levels reduce with age (Matthews, Cauley, Yaffe, & Zmuda, 1999; Sternbach, 1998). For example, testosterone in males is estimated to decrease by approximately 100 ng/dl per decade (Driscoll & Resnick, 2007). It is established that both testosterone and oestrogen are not just limited to determining gender dimorphism, but also play a significant part in the release and metabolism of neurotransmitters (Genazzani, Pluchino, Luisi, & Luisi, 2007). Decline in levels of these hormones contribute to the ageing of the central nervous system through their interaction with steroid hormone receptors in the brain. These are intracellular receptors which are sensitive to steroid hormones and trigger gene expression. They are found in the plasma membrane, intracellular fluid as well as the nuclei of cells.

Depending on their type and location they either bind with the steroid hormone and move to the nucleus or stay within the intracellular fluid and migrate to the nucleus when activated.

Estrogen plays an important part in neuronal and glial cell functioning (Schumacher et al., 2000). Animal studies have demonstrated the protective effect of estrogen on temporal order recognition memory (TORM) in female rats. Wei et al. (2014) subjected both male and female rats to one week of repeated restraint stress. Female rats demonstrated no negative effects of this intervention on TORM a process normally associated with the prefrontal cortex. However, when oestrogen receptors were inhibited in the prefrontal cortex in the female rats, performance in TORM declined as per males.

Menopause relates to the period in a female's life when the ovaries stop producing progesterone and oestrogen which subsequently leads to infertility. This period is also associated with a drop in cognitive performance over the relatively short period of time of the menopause as demonstrated through poorer performance in the Symbol Digit Modalities test and the East Boston Memory test (Greendale et al., 2009). Such observed cognitive decline might be considered a result of any number of factors related to ageing itself. However, studies investigating reproductive senescence, independent of age, show a decline in some cognitive functioning (Hogervorst, 2012; Ryan et al., 2014).

Receptors for testosterone are mainly found in the hippocampus and the prefrontal cortical regions. Further, the granular layer of the hippocampus is sexually dimorphic with a tendency towards greater size in males. Evidence suggests that the decline in testosterone for older males represents a risk for cognitive decline, mild cognitive impairment and subsequently Alzheimer’s disease (Barrett-Connor, Goodman-Gruen, & Patay, 1999; Moffat et al., 2004). Furthermore, females treated with testosterone exhibit increased hippocampus size as well as exhibiting increased spatial performance (Roof & Havens, 1992). Given the relationship between the hippocampus and spatial learning and memory, it is unsurprising that a relationship between decline in levels of testosterone (having receptors in this region) and spatial ability is found. For example, testosterone levels have demonstrated a positive correlation with performance in a reference memory version of the Morris Water Maze with higher performance in castrated rats who had been provided with testosterone injections and compared to castrated controls (Spritzer et al., 2011). Such effects have been found in both animals (Gordon & Lee, 1986; Neave, Menaged, & Weightman, 1999) and humans (for a review, see: Kimura, 2002). However, caution must also be applied when generalising the effects of non-human studies to humans. In animal studies, supplementation is almost always applied to the castrated animal, therefore the testosterone supplement is in fact a replacement of a complete absence of the steroid. The baseline amount of testosterone, even in older human adults, is considerably higher before augmentation. Furthermore, any relationship declining testosterone in older adults may have with cognitive ability may demonstrate the confounding effect of other age related factors.

Testosterone supplementation in human males has demonstrated a number of cognitive effects. In cognitively intact humans, studies on younger males are limited but available. For example, testosterone supplementation and controlled endogenous production in 61 males adults between the age of 18-35 demonstrated an increase in visual-spatial performance using a checkerboard test (Bhasin et al., 2001). In cognitively intact older males, the trend appears to be one of improved spatial performance and conflicting results regarding verbal performance. For example, improved spatial performance was demonstrated in a group of 56 healthy older adult males who were supplemented with testosterone over a three month period (Janowsky, Oviatt, & Orwoll, 1994, for a review see: Driscoll & Resnick, 2007). As per younger adults, the number of studies in which patients with MCI or AD have been supplemented with testosterone is limited but positive effects for testosterone supplementation have been found. For example, males aged between 63 and 85 were grouped according to their status as having either MCI or AD. They were provided with a six week course of testosterone supplementation, after which improvements in both spatial and verbal memory were demonstrated (Cherrier et al., 2005).

1.11.9 Other risk factors

In addition to the biological factors which normally go hand in hand with ageing, there are a number of factors which are related to ageing but are also synonymous with lifestyle-related risk factors such as diet and alcohol consumption.

1.11.10 Hypertension

Hypertension or high blood pressure is one of the more modifiable risk factors related to cardiovascular disease (Burt et al., 1995). However, it is extremely common within industrialised nations (Whelton, 1994). Within the brain, tight junctions of endothelial cell wall between the capillaries and venules, supported by astrocyte cells, form the blood brain barrier (Janzer & Raff). Chronic hypertension leads to the breakdown of the capillaries and is associated with neuronal damage and subsequent cognitive impairment (Farkas et al., 2000). In light of the relationship between hypertension and cognitive impairment, the relationship between hypertension and Alzheimer's disease has also been investigated, since blood pressure tends to rise with age. Risk of hypertension is also higher in those with unhealthy lifestyle habits such as drinking and smoking, are overweight or have a family history of high blood pressure. However, age appears to be the predominant risk factor with 65% of Americans age 60 or over being diagnosed with high blood pressure ("Who Is at Risk for High Blood Pressure?," 2012). Therefore, hypertension is very much an age-related risk factor. In a study of 700 individuals diagnosed with Alzheimer's disease, evidence was found of an association between hypertension and increased cognitive decline after controlling for baseline disease severity (odds ratio 1.6, p<.05; Bellew et al., 2004). Further, in those individuals who were less than 65, those with hypertension were more likely to have an increased cognitive decline than those who were not diagnosed with hypertension (odds ratio = 6.9, p<.005). In an observational study with over 1800 participants, it was found that those taking blood pressure medicine were less likely to have dementia (Guo et al., 1999) as well as being less likely to develop it over the three-year period of the study. Those individuals with dementia at the beginning of the study not taking blood pressure medicine displayed a twofold faster rate of decline in the MMSE scores over the period of the study than those taking blood pressure medicine.

1.11.11 Oxidative Stress

The rate-of-living hypothesis states that metabolic rate of a particular species determines its lifespan. What was not known at its inception was the mechanism underlying the correlation. This changed a decade later when superoxide dismutase was discovered. The sole purpose of this enzyme appeared to be the removal of superoxide anions, otherwise known as free radicals (Finkel & Holbrook, 2000). These endogenous oxygen containing molecules are generated within cells as a result of metabolism and have the capability to damage complex molecules such as DNA proteins or fats (Wu & Cederbaum, 2003). As such, the build-up of free radicals or oxidative stress became synonymous with the rate of living hypothesis since it provided an explanatory mechanism.

Given that the brain consumes roughly 20% of oxygen within the body, it is especially prone to oxidative damage. Furthermore, the brain contains high concentrations of phospholipids. These are more susceptible to oxidative damage and in conjunction with the high metabolic rate of the brain where they are found in greater numbers, the risk becomes even greater than in other parts of the body (Lovell & Markesbery, 2007). In a study involving 338 individuals, thiobarbituric acid, a marker of free radical damage, was observed in significantly greater levels in the those participants with a neurodegenerative condition (Serra et al., 2009). Specifically, the damage caused by free radicals to DNA is related to mild cognitive impairment and Alzheimer’s disease (Lovell & Markesbery, 2007; J. E. Simpson et al., 2014). Further, a study with 45 participants with Alzheimer’s disease and 28 cognitively unimpaired controls demonstrated significantly increased levels of oxidative damage, as demonstrated by increased protein oxidation in their blood plasma (Bermejo et al., 2008). Participants also demonstrated significantly reduced levels of glutathione, an endogenous antioxidant.

The above section has summarised a number of factors associated with ageing that are associated with the declining general cognitive function and psychological well-being. What is not so clear is how the relationship between any of these factors and cognition over age is moderated. The following section describes a number of theories and models which attempt to describe the mechanisms underlying this function.

1.11.12 The cognitive effects of age

As the physical brain declines, the computational effectiveness of the brain also declines. The biological ageing of the brain manifests itself in changes within a number of cognitive domains. The good news is that relatively small amounts of changes are observed in middle to late adulthood (35-75) in performance in procedural memory or priming tasks (Bäckman, Small, Wahlin, & Larsson, 1999). Further, a positive gradient has been observed for semantic memory over age with a significant increase between middle age (35-50) and young old (55-65)with no discernible difference between young old and old-old (70-80) (Nyberg et al., 2003). However, decline is observed in explicit memory and attention as well as perceptual and spatial abilities with age (Raz et al., 2000; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998) with episodic memory most affected by age (Bäckman, Small, Wahlin, & Larsson, 1999; Nyberg et al., 2003) followed by working memory (Park et al., 2002). However, the extent to which both episodic and working memory are affected by age is the subject of debate since longitudinal data paint a far less depressing picture than cross-sectional data, except when practice effects are adjusted for (Nyberg et al., 2012). When the appropriate controls for practice effects have been applied to longitudinal data, the results demonstrate a decline in episodic memory from around 65 years of age.

Relatively few longitudinal studies have been carried out specifically on working memory. However, for abilities such as reasoning which are highly related to working memory, a number of longitudinal studies have demonstrated poor performance over age. For example, in performing the tower of Hanoi task, the amount of moves carried out by the participants to complete the task increased as the age of the participant increased (Rönnlund, Lövdén, & Nilsson, 2001). Furthermore, in keeping with reports of episodic memory decline during age, performance on an episodic memory task was also a significant predictor. One of the theories proposed to account for the loss of working memory is the inhibition-reduction theory (Zacks, Hasher, & Li, 2000). This theory implicates working memory with the ability to efficiently inhibit irrelevant information. Age-related decline of inhibitory processes would therefore lead to leaking of non-relevant information into working memory and therefore reduce the space available for relevant information. This theory was tested by Bowles and Salthouse (2003) who found a relationship between scores on working memory span tasks, in which participants were asked to remember the last digit from a previous maths problem, and the proactive interference that was experienced from subsequent trials. Furthermore, it was also found that there was a significant difference between older and younger participants in the amount of proactive interference experienced. This study demonstrated decline in working memory in older adults as well as suggesting that the origins of this decline lay in reduced efficiency of central executive processing.

A general explanation for the cognitive deficits observed in older adults is that they are the result of an overall decline in processing speed. The ability, for example, to match two identical numbers in a list starts off slowly in young children, speeds up until late teens and then starts to decline from the 40s onward (Woodcock, Johnson,

& Mather, 1990). Such a reduction in speed at the behavioural level has been postulated to be the result of reductions in the speed of neural processing which in turn results in a reduction in the transfer speed of information along the neural pathways as well as a reduction in synchronisation of neural computation (Salthouse, 1985). This time delay not only affects perceptual matching tasks but is an explanation for the reduced performance of older adults in a number of perceptual tasks. Salthouse (1996) explains the relationship between reduced processing speed and poorer performance in terms of the limited time mechanism and the simultaneity mechanism. The limited time mechanism relates to the inability to perform later cognitive operations due to time being taken up by the performance of earlier operations. The simultaneity mechanism describes a relationship between cognitive performance and speed of processing. Poor performance is due to the inability of latter processes to access the products of prior processes due to the time that these previous processes have taken.

An alternative view of the decline in speed of processing is that it is due to changes in the decision-making processes. This gives a backend view of slow response times in which non-decision processes do differ but critically, they are also due to a more conservative decision criteria (Ratcliff, Thapar, & McKoon, 2004). In the case of Ratcliffs’ diffusion model (1978), this means that a greater amount of evidence needs to accumulate and therefore a greater time is required to make a decision.

1.12 Related theories

There are a number of theories of cognitive ageing which will be relied upon in the investigation of CR. The following section introduces these theories and puts them in the context of the studies is this thesis.

1.12.1 HAROLD

The second and third chapters of this thesis cover the neural compensation sub-concept of CR. In doing so they deal with one thread of evidence that has contributed to reinforcing hemispheric asymmetry reduction in older adults (HAROLD; Cabeza, 2002). This was the observation that older adults who were able to maintain a particular cognitive ability demonstrated bilateral activation in frontal regions whereas their younger counterparts demonstrated unilateral activation. This model contributes to the neural compensation theory of CR as the pattern was interpreted as the engagement of additional brain areas to prop up declining processing in the original hemisphere given the neurological decline described at the beginning of this chapter (Cappell, Gmeindl, & Reuter-Lorenz, 2010; Reuter-lorenz & Lustig, 2005). Chapter two of this thesis provides a computational model to describe this compensatory process using current understanding of two biologically based neural processes, the ability to monitor conflict based on task demand and the ability to switch processing streams from a single hemisphere to dual hemisphere processing.

1.12.2 CRUNCH

Compensation Related Utilisation of Neural Circuits or the CRUNCH hypothesis (Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz & Cappell, 2008) expands on the concept of across hemisphere compensation and relates to both the general cortical over-activation during ageing and the concept of CR, all of which are described above. Its purpose is to describe the relationship between certain brain activations and increases in task performance. As its name suggests, the activation (or reduced deactivation) observed relates to the contribution of neural circuitry, either across hemispheres or within them. Furthermore, the hypothesis suggests that this neural circuitry is age invariant.

Given the variety of over activations, as reported above with both the HAROLD and PASA observations, it is unlikely that any increases observed in relation to age-related activations is down to a single source (Reuter-Lorenz & Cappell, 2008). One of the principles behind the CRUNCH hypothesis and the reason why it represents an evolution of the across hemispheric view of compensation is that compensation, according to the CRUNCH hypothesis, is related more to task demand than to ageing. However, ageing very much has its place in this hypothesis since age-related decline leads to the needs to recruit at an objectively lower task demand (Reuter-Lorenz & Cappell, 2008). Therefore, this hypothesis suggests that when subjective task difficulty is matched, brain activation should appear very similar between older and younger participants. The answer to this question was achieved by assessing the memory capacities of individuals in both young and old groups and factoring this information in to control for the age gap (Schneider-Garces et al., 2010). This was achieved by measuring working memory capacity using the same task that was used to assess brain activity, the Sternberg task. The results demonstrated that when task demand was equated through the measure of working memory span, those individuals whose estimation of memory span was lowest demonstrated more bilateral brain activation than those who had scored higher, regardless of age. Such a finding adds weight to the idea that the neural circuitry exists in younger participants to implement the compensatory activation and it is not the result of neural reorganisation occurring later in life. The focus of chapter three is to investigate this phenomenon from a perceptual modality with the use of a visual field paradigm.

1.12.3 STAC

The Scaffolding Theory of Ageing and Cognition (STAC) posits that the additional frontal activation observed as individuals get older is the result of neural reorganisation as a response to neurological decline. The original STAC model (Park & Reuter-lorenz, 2009) offered a compensatory view given the engagement of supplementary neural circuitry whilst also providing a nod to neural reserve through the enhancement of scaffolding via engagement with learning activities and cognitive training. The mechanism for the enhancement of scaffolding is not described but one must assume the involvement of those neural pathways already involved in the particular cognitive functions being trained. Therefore, compensation in terms of recruitment of other brain regions is not applicable in this case. This model also illustrates an interaction between environmental and biological factors. As with the CRUNCH model, evidence from younger adults showing additional recruitment in the face of subjectively increased task demand caused the authors to conclude that such mechanisms exist throughout life span and are consequently adopted in older age to maintain already established cognitive function. Further, these processes can be moderated by individual differences in the ability of ‘brain maintenance’ (Nyberg et al., 2012). This relates to differences in efficiency in brain mechanisms which are responsible for an individual’s ability to withstand cognitive ageing. A revised version of STAC (STAC-R; Reuter-Lorenz & Park, 2014) implicates two new constructs, neural resource enrichment and neural resource depletion as direct influencers of age-related neural reorganisation which are cumulative over lifespan. Neural resource enrichment expands the original environmental influences of enrichment to compensatory scaffolding to encompass lifestyle and social activities. Neural resource depletion, on the other hand, relates to those risk factors described at the beginning of this chapter such as diabetes and smoking. Chapters four and five of this thesis investigate multilingualism as one aspect of neural reserve, known within the STAC-R model as neural resource.

1.13 Summary

This thesis contains four chapters that relate to investigations into Cognitive Reserve (CR). However, a clear division between the studies in chapters two and three and those studies in chapters four and five exists. This division reflects two theoretical standpoints within cognitive reserve, neural reserve and neural compensation. Whilst both theoretical standpoints represent the notion of offsetting cognitive reserve, each one relates to different mechanisms, as described in this chapter. As such, this thesis could be viewed as containing two parts with the division being between chapters three and four. In order to provide a rounded picture of cognitive reserve from two different perspectives, the two chapters relating to neural compensation and the two chapters relating to neural reserve both contain descriptions of a computational and a behavioural study.

This introduction has considered a picture of ageing from both a biological and cognitive perspective. It is also described those factors which may contribute to the mitigation of such decline. Evidence, both behavioural and imaging based, have demonstrated the capacity for a degree of compensation as an offset to both normal ageing and dementia pathology. Such compensation may not simply be the result of genetically unmodifiable biological systems but may also relate to a number of external factors. With specific regard to the notion of CR, the question still very much remains as to what it is. This thesis investigates CR from the perspective of its two biggest facets, neural reserve and neural compensation. Chapter two proposes a model of neural compensation as experienced through the HAROLD model in which asymmetric brain activity is reduced over age. Chapter three expands on this concept by exploring the proposals put forward by both the CRUNCH and SPAN models relating to the idea that younger adults are capable of recruiting resources from the contralateral hemisphere, it is simply a case that task demand under normal circumstances does not require this. Chapters four and five relate to neural reserve in the context of environmental proxies of the ability to offset the cognitive decline, in this case multilingualism. Chapter four describes a neural network model of bilingualism and compares it to a monolingual network over lifespan. Chapter five describes two behavioural studies in which the multilingual ability of participants is related to their performance into tasks requiring executive function. The final chapter provides a discussion of the findings of all the investigations in this thesis. The next section provides an overview of the studies carried out within this thesis.

1.14 Expanded Overview

1.14.1 Study one

The overall aim was to provide a mixed methodology approach to be mechanisms underlying cognitive reserve. The first study in this thesis investigates one of the sub-theories of cognitive reserve, neural compensation by looking at the increased flow of resources between the two cerebral hemispheres under certain instances of increased task demand. A model is proposed which combines the properties of two neural regions to produce a mechanism which describes the flow of resources between hemispheres given increased task demand. Data patterns produced by the model mirrored the results of behavioural studies which have shown an advantage in older adults for presenting a difficult task across hemispheres.

1.14.2 Study two

Study two continues to investigate the sub theory of neural compensation. A behavioural investigation was carried out to explore the idea that the increased flow of resources between hemispheres as a compensatory mechanism was the result of subjectively increased task demand rather than a result of ageing. A new variation of the visual field paradigm used in study one was used in which task demand was taken to high levels. Younger adults were used in this study to see if they demonstrated an advantage for between hemisphere processing when task demand was high enough. The results demonstrated no advantage for the presentation of difficult task across the hemispheres. These results contribute to the argument that this particular type of compensation is the result of the ageing process rather than an inherent mechanism.

1.14.3 Study three

The next two studies described in this section investigate the second sub theory of cognitive reserve, neural reserve. There may be a link between bilingualism and cognitive reserve due to reported improvements in executive control processes by bilinguals. Study three investigates the generation of inhibition within monolingual and bilingual networks to investigate how this may occur. Two neural network models are presented. The first investigates differences in distribution of lexical representations between monolingual and bilingual neural networks as a proxy of inhibitory processing. The second simulation looks at semantic representations and their spacing in monolingual and bilingual neural networks. In the second simulation, a longitudinal perspective is taken with ageing represented by an incremental change in gain in the sigmoidal transfer function. Brain reserve, described below, is also represented in both models by changes in size of the hidden layer. The results demonstrated a negative relationship, and therefore inhibitory activation, between weights from language tags when different languages are activated. Further, the simulations demonstrate differences in spacing within the representations in the bilingual networks. These results are interpreted in relation to retrieval induced inhibition is a result of greater overlap of representations.

1.14.4 Study four

Robust evidence exists for a relationship between bilingualism and cognitive reserve. The bilingual advantage in younger adults provides a clue as to how this particular proxy of cognitive reserve is instantiated. The final study in this thesis represents two large-scale investigations in which the main aim is to investigate the relationship between bilingualism and executive control processes. Bilingual language use and performance in two tasks involving executive control were measured as well as a questionnaire which took into account more traditional measures of cognitive reserve. The first investigation in the study looked at Stroop task performance in the second study task switching performance. The results of this study demonstrated very little predictive relationship between measures of bilingualism, traditional proxies of cognitive reserve, and performance on the executive control tasks. The results of this study support current research which refutes a bilingual advantage. The persistence of a relationship between bilingualism and cognitive reserve, however, means new investigative avenues need to be sought.

Chapter two: A Computational Model of Neural Compensation[1]

2.1 Introduction

This chapter describes a proposed mechanism and an accompanying computational model of one sub-concept of cognitive reserve, neural compensation. Neural compensation, as described in Chapter one, is a process by which areas of the brain, not normally responsible for particular function, come online in order to provide additional processing resources for that function (Stern, 2003). The imaging observation common with neural compensation is the increase in activation in alternative brain regions in older rather than younger adults in response to a particular task (Morcom & Johnson, 2015). This additional activation is sometimes accompanied by a relationship with higher performance within those older adults who demonstrate the most activation (e.g. Reuter-Lorenz & Cappell, 2008). The results from a variety of imaging studies provide evidence for a change in activation profiles during aging. For example, the Posterior to Anterior Shift in Activation model (PASA; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008) describes observations in which older adults demonstrate weaker activity than younger adults in occipitotemporal regions. This is normally accompanied by greater activity in the anterior regions for the older adults (Grady et al., 1994). Furthermore, this activity is

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[1] Aspects of this chapter have been published in: Mayor, J. (2014). *Computational Models of Cognitive Processes: Proceedings of the 13th Neural Computation and Psychology Workshop* (Vol. 21). World Scientific.

accompanied by results which suggest that the anterior activation is compensatory (Bangen et al., 2012).

This chapter is concerned with one specific aspect of neural compensation. This is known as the Hemispheric Asymmetry Reduction in Older adults (The HAROLD model; Cabeza, 2002). This model relates to the observation that activation that was once restricted to one brain hemisphere in younger participants carrying out a particular task, shifts across to the contralateral hemisphere thus creating a reduction in asymmetry. This chapter starts by reviewing the HAROLD observations in general and then moves on to visual field based studies as evidence for bilateral recruitment. The introduction continues with a discussion of the neural mechanisms involved in cognitive compensation via hemispheric recruitment. A description of the model and how these mechanisms are implemented computationally, completes the introduction to this chapter.

2.1.1 The HAROLD model

As a form of cognitive reserve, neural compensation relates to the capacity of one region of the brain to compensate for a decrease in resources in another (Barulli & Stern, 2013; Stern, 2009). For example, a PET study examining differences in regional activity between older and younger adults carrying out a word-pair recall task demonstrated higher activation in older adults than younger adults in several locations (Cabeza et al., 1997). These increases were in some cases combined with a decrease in activation in those regions normally associated with carrying out the task in younger adults. The authors favoured an explanation first provided by Grady et al., (1994) in that the change in activation profile over age was the result of functional compensation.

Since these initial observations, a number of imaging studies have demonstrated similar findings in terms of increased bilateral activation over age. Reuter-Lorenz et al. (2000) used both verbal and spatial memory tasks with groups of older and younger female adults. In the verbal task participants were required to store four target letters for three seconds and indicate whether or not a probe letter was part of the initially remembered target letters. The same sort of procedure was used for the spatial task except the locations of dots were used instead of the letters. PET subtraction was made between scans performed during these trials and a baseline condition which included all of the components except for the matches. For both verbal and spatial tasks a pattern of bilateral activation in the frontal cortex was observed in older adults whereas activation for the younger participants was much more unilateral in nature. Furthermore, of those older adults, there was a positive relationship between the amount of bilateral activation demonstrated and how quickly those adults performed. Bilateral activation in older adults was also observed in both hemispheres relating to Brocas region (BA44) for the verbal tasks as well as bilateral activation in the supplementary motor area (SMA) for the spatial tasks. Cabeza (2002) provided a comprehensive review of the evidence from imaging studies demonstrating hemispheric asymmetry (**Error! Reference source not found.**) and labelled such phenomena as Hemispheric Asymmetry Reduction in OLder Adults (HAROLD). Since this time, a number of other studies have also demonstrated bilateral activation in older adults. In a general review carried out in order to establish biological correlates of successful cognitive ageing (Eyler, Sherzai, Kaup, & Jeste, 2011), a number of examples of the HAROLD model were established. Articles published between January 1989 and December 2009 that used imaging techniques to examine neural functioning in relation to cognitive tasks with at least one group of healthy older individuals (mean age > 60 years) were included. Within the total of 80 articles which fitted these criteria, a number of cognitive paradigms were included, such as resting paradigms, working memory tasks, and inhibitory processing with episodic learning and memory tasks being the most frequently reported. Within these studies, 16 described the HAROLD pattern, referred to by the authors as overactivation in a homologous region in the opposite hemisphere. The HAROLD pattern was found in older compared to younger adults in a wide variety of tasks, such as likeability judgements on faces (Krendl, Heatherton, & Kensinger, 2009), recognition for animate and inanimate semantic words (Duverne, Motamedinia, & Rugg, 2009), semantic judgement (Bergerbest et al., 2009), and working memory for auditory stimuli (Grady, Yu, & Alain, 2008).

The characterisation of the activation profile from imaging studies reflecting HAROLD is largely descriptive (Morcom & Johnson, 2015). In order to provide a quantitative investigation of the specific HAROLD pattern, Berlingeri, Danelli, Bottini, Sberna, and Paulesu (2013) used a statistical approach which considered the whole brain volume to analyse fMRI images gained from 24 healthy elderly and 24 young control participants carrying out four tasks. These were picture naming, sentence judgement, picture recognition, and sentence recognition. The authors considered a genuine HAROLD pattern was one in which lateralised activation that was observed in younger adults was reduced in concert with additional contralateral activation in older adults (Figure 2.1). In applying this particular definition of the HAROLD pattern, there was found to be a smaller number of activation clusters over all of the participants on some of the tasks than would have been predicted by previous studies. For example, in relation to a group-based comparison, only 20% of the activation clusters in the picture naming task demonstrated this pattern and only 50% of clusters in the sentence judgement task showed the genuine HAROLD pattern.

Berlingeri et al., (2013) extended their results to other studies in which the HAROLD pattern has been observed (Cabeza, Anderson, Locantore, & McIntosh, 2002). They postulated that many of them demonstrate a pseudo HAROLD pattern in which activation in the contralateral hemisphere, observed in relation to maintained task performance, is *additional* to rather than *compensating* for a decline in activation. Whilst this suggestion means that increased activation in the contralateral hemisphere is not complemented with decreased activation in the hemisphere normally associated with a particular function, there is still evidence to suggest that the contralateral activation was compensatory. This is because the authors also observed that increases in activation demonstrated in association with the increase in activation in the contralateral hemisphere were related to task demand. Therefore, such contralateral activation, rather than a reaction to a decline in neural resources in a single hemisphere, still appears to be compensatory in that it may be the result of recruitment when task demand exceeds the available resources in a single hemisphere. This observed recruitment of additional resources in response to increased cognitive load may be more compatible with the Compensatory-Related Utilisation of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008) described below. Furthermore, it is the mechanism which engages an exchange between the two hemispheres in the face of increased task demand rather than the distribution of the activation over age which is the focus of the model in this current chapter.

Table 2.1: Table adapted from Cabeza (2002) showing examples of the results from imaging studies which demonstrate the HAROLD pattern. '+' and '-' relate to task-related activation increases or decreases respectively compared to baseline.

	Younger		**Older**	
Imaging technique, materials and task	**Left**	**Right**	**Left**	**Right**
Episodic Retrieval				
PET: Word-pair cued recall (Cabeza et al., 1997)	-	++	+	+
PET: Word-stem cued-recall (Backman et al., 1997)	-	+	+	+
PET: Word recognition (Madden et al., 1999)	-	+	+ +	+ +
PET: Face recognition (Grady et al., 2002)	-	++	+	+
Episodic Encoding/Semantic Retrieval				
fMRI: Word-incidental (Stebbins et al., 2002)	++	+	+	+
fMRI: Word-intentional (Logan & Buckner, 2001)	++	+	+	+
fMRI: Word-incidental (Logan et al., 2001)	++	+	+ +	+ +
Working Memory				
PET: Letter DR (Reuter-Lorenz et al., 2000)	+	-	+	+
PET: Location DR (Reuter-Lorenz et al., 2000)	-	+	+	+
PET: Number N-back: (Dixit et al., 2000)	+	+++	+ +	+ +
Perception				
PET: Face matching (Grady et al., 1994)	-	+	+ +	+ +
PET: Face matching (Grady et al., 2000)	+	+++	+ +	+ +
Inhibitory Control				
fMRI: No-go trials (Nielson, Langenecker, & Garavan, 2002)	-	+	+	+

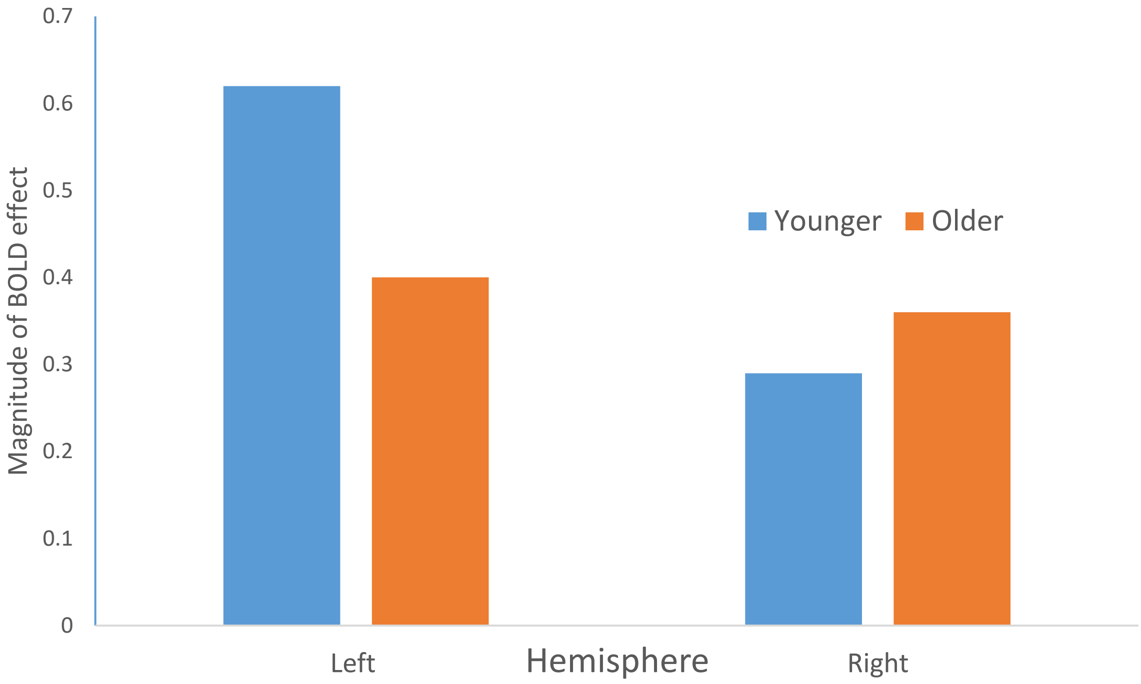

Figure 2.1: The true HAROLD pattern (adapted from Berlingeri et al., 2013). Left and right relates BOLD response to a particular task in the left or right hemisphere. Blue bars relate to younger participants and orange bars relate to older participants. The decline in left BOLD response is offset by an increase in BOLD response in the right hemisphere.

One account of HAROLD observation may be that instead of an age-related, biologically driven recruitment process, the bilateral activation observed in older adults is the result of a change in cognitive strategy. In the case of the study by Reuter-Lorenz et al. (2000), there was no significant difference between accuracy between groups, but older subjects wgere significantly slower in their responses. This may be evidence of what is known as the speed-accuracy trade-off in which accuracy is forgone in the effort to be faster at a particular task (Garrett, 1922) and may manifest itself in activation of different regions, namely the pre-Supplementary Motor Area (pre-SMA; Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010). Of note is the pre-SMA was an area demonstrating some bilateral activation in older adults in the study by Reuter-Lorenz et al. (2000). Another possible strategy change would be the reliance on additional knowledge to increase performance (Hedden, Lautenschlager, & Park, 2005). However, in the study by Reuter-Lorenz et al., (2000) both older and younger adults reported using the same verbal rehearsal strategies rather than spatial strategies. Similarity of error patterns for both groups appeared to reinforce this assertion. In addition, bilateral activation has also been observed in simpler perceptual motor tasks for which utilisation of a different cognitive strategy would be ineffectual (Calautti, Serrati, & Baron, 2001).

While strategy change may be one alternative to a suggestion of neurologically based compensation, an alternative explanation offered of the HAROLD pattern is that it is due to dedifferentiation (Berlingeri et al., 2013; Collins & Mohr, 2013). In this process, a set of discreet cognitive functions reorganise into less specialised functions due to the decrease in resources associated with aging. Another way of viewing dedifferentiation is that it is the inverse process of *differentiation* (Garrett, 1946) in which the developing brain moves from a generalised set of cognitive abilities to discrete cognitive functions. Evidence for dedifferentiation itself is seated in increased correlations among different cognitive measures with age (Baltes & Lindenberger, 1997; Babcock et al., 1997; Cabeza et al., 2002). This suggests a ‘collapse’ of such distinct cognitive functions into a more generalised function that carries out all of the tasks albeit in a less specialist, and therefore less effective way. This theory was also demonstrated as computationally viable through the decomposition of ‘what’ and ‘where’ generalised tasks into a modular neural network (Jacobs et al., 1991). Although dedifferentiation is viewed as a negative consequence of aging, it may be the most cost-effective method of providing the best cognitive functionality given the resources available. Furthermore, whilst being billed as a proposition at odds with a compensatory view of bilateral activation in older age (Eyler et al., 2011) there may be some complimentary aspects to both positions (Burianová, Lee, Grady, & Moscovitch, 2013). For example, at a biological level, dedifferentiation suggests that an increased amount of neural tissue is recruited for the task. Therefore, HAROLD, neural compensation, and dedifferentiation reflect the same consequence of ageing.

Given that alternative explanations do exist for an increase in activation in the contralateral hemisphere, the most obvious way to link it to compensation is to be able to associate it with higher performance. One way of doing this is to manipulate the way a particular task is seen by a particular type of participants. By categorising older adults into high and low performing groups, Cabeza, Anderson, Locantore, and McIntosh (2002) were able to manipulate the subjective difficulty of the same task. In this study, a number of participants were pre-screened using a battery of tests measuring a number of cognitive functions, including executive processes. From the results and age information, participants were separated into three groups. All younger participants were placed in a single group (mean age = 25.3) whilst older participants were split into old-high (mean age = 68) and old-low (mean age = 69.9). The participants were required to remember a list of twenty-four unrelated word pairs. After this, under scanning conditions, they were presented with one of the words in the pair and the participant was required to recall the other word. The comparison task was based on a source recognition task in which participants were required to state whether or not they had seen or heard previously presented words by stating a word recalled in the recall task. The authors hypothesised that if greater bilateral activation was an indication of dedifferentiation then it would be more prevalent in the old-low subgroup. However, greater bilateral activity in the old-high group would suggest that the increase in bilateral activation is compensatory in nature. The results demonstrated that activation in the PreFrontal Cortex (PFC) was right lateralised in young and old-low participant groups with the old-low group demonstrating a low performance than the younger adults. The old-high group performed best out of the two older groups and, unlike the old-low group, demonstrated bilateral activation. As such, bilateral activation was associated with higher task performance between the two groups of older adults. This was interpreted by the authors as clear evidence for a compensatory view of bilateral activation. The results of this study suggest that recruitment of the contralateral hemisphere is related to an advantage in task performance for older adults. It also appeared that a mechanism exists to recruit the necessary additional resources when task demand reaches a particular threshold and that this mechanism performs less effectively in the old-low group.

The association between increased bilateral activation and better performance within older adults demonstrates a capability that may preserve some function with increased age (Cabeza et al., 2002). The Compensation Related Utilisation of Neural Circuits Hypothesis or CRUNCH (Reuter-Lorenz & Cappell, 2008) suggests that, up to a point, at any given level of task demand older adults will recruit greater resources than younger adults to carry out processing. As such, when task demand is held constant between older and younger participants, differences in hemispheric activation can be observed but performance should be equivalent. However, this can only go up to a point. In their study Cappell, Gmeindl, & Reuter-Lorenz, (2010) observed that older adults demonstrated increased right frontal activity on a verbal working memory task in which both old and young participants only had to remember 2-4 items. Beyond this level of difficulty, activation was reduced and performance dropped. Given that older adults will use more resources for the same level of task demand, there will inevitably be a point at which demand outstrips resource supply. Similar observations were also found with the n-back task in which older participants demonstrated increased bilateral activation in BA9 at low levels of task difficulty (1-Back) which disappeared when task performance decreased (V. Mattay et al., 2006).

Much of the imaging support for the HAROLD model comes from the application of multivariate methods of image analysis. One commonly used example is that of partial least-squares analysis (for a review, see: Krishnan, Williams, McIntosh, & Abdi, 2011). However, a novel method of multivariate image analysis was employed by Morcom and Friston (2012) who used multivariate Bayesian analysis to demonstrate a shift to bilateral activation in episodic memory encoding. They scanned 14 young adults and 14 older adults whilst carrying out a recognition memory test in which participants were initially required to make living or non-living decisions about a series of nouns. Participants were then required to make recognition judgements about the stimulus provided. Half of each group were scanned doing so after 10 minutes and the other half were scanned after 40 minutes. Multivariate Bayesian decoding of the images demonstrated that compared to younger adults, successful episodic memory encoding was associated with greater and more diffuse bilateral activation in the PFC. This study demonstrates increased validity of the compensatory view of the HAROLD model through the application of modern Bayesian statistical methodology to imaging studies. The following section provides evidence in addition to imaging studies for the existence of a mechanism that allows interhemispheric processing under specific conditions.

2.1.2 Transcranial magnetic stimulation (TMS) evidence

Imaging studies provide compelling evidence for a capacity for recruitment of additional resources from the contralateral hemisphere. However, what they cannot avoid is the correlational nature of the association between the observed contralateral activation and performance. To this end, transcranial magnetic stimulation (TMS) studies extend the evidence for the causal role of contralateral brain regions in maintaining performance in aging adults. Rossi et al. (2004) gave 66 healthy (37 ‘young’ and 29 ‘old’) subjects repetitive TMS (rTMS) to either the right or left dorsolateral prefrontal cortex (DLPFC) whilst carrying out encoding and retrieval trials of an episodic memory task. Consistent with the Hemispheric Encoding Retrieval Asymmetry (HERA) hypothesis (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994), Rossi et al. (2004) found that rTMS applied to the right DLPFC interfered more with task performance than rTMS applied to the left in the young group. However, in the older group, while right hemisphere activation was predominant throughout the retrieval phase, rTMS applied to the left DLPFC was associated with a drop in performance. This could be interpreted as the interference with normal compensatory processes that occur during aging. Transcranial magnetic stimulation was also used on a group of healthy older adults during encoding and retrieval of word pairs. Based on their performance in this task, participants were divided into two groups; high and low performing. TMS was applied to the Brodmann area 46 in both left and right hemispheres during both encoding and retrieval. As with the previous study by Rossi, (2004) results were largely in line with the HERA model for recollection but this was more prominent in some of the lower performing older adults. More robust results were observed with high performing participants in the encoding phase with stimulation to the left DLPFC which affected performance more than application to the right DLPFC, suggesting that the disruption to the additionally recruited area was a contributing factor to the performance of the individual. These studies demonstrate that the additional activation in the contralateral hemisphere is related to task-based recruitment rather than unrelated processes for which disruption by TMS would not cause a significant effect on performance. Behavioural evidence for an across hemisphere processing advantage is discussed below.

2.1.3 Visual field studies

In order to assess any differences between hemispheres in terms of lateralised functions and the HAROLD model, Collins and Mohr (2013) gave 20 older and 20 younger participants tasks which were normally lateralised to either the left or the right hemisphere. Lateralised lexical decisions were associated with left hemisphere and decisions on chimeric faces were associated with the right hemisphere. A reduced advantage for lexical decisions presented to the right visual field (processed in the left hemisphere) compared to the left visual field were found for older adults compared to younger adults with mixed results for chimeric faces presented to the left visual field. The difference between left to right and right to left recruitment between hemispheres suggests a differences in the capability to provide additional resources. Therefore, as well as supporting the HAROLD, these findings also support the idea of increased right hemisphere decline during ageing as suggested by the Right Hemi-Ageing Model (RHAM; Brown & Jaffe, 1975).

The focus of study in this chapter is a visual field study carried out by Reuter-Lorenz et al. (1999) as a variant of a letter matching task developed by Banich & Belger

(1990). This particular technique relies on presentation of stimulus across hemispheres which is then compared with tachiscopically presented stimulus to a single hemisphere. This method is enabled by the idea that information presented to either the left or the right visual field is processed in the visual cortex of the contralateral hemisphere. As such, presentation of a stimulus in each of the visual fields which is quick enough to disallow any saccadic eye movement across the visual fields means communication across the hemisphere must take place in order to process the stimuli. Reuter-Lorenz et al. (1999) projected a series of target letters over both visual hemi-fields (each hemi-field is half of the total visual field) of both older and younger participants (Figure 2.2). A probe was also concurrently displayed in one of the hemi-fields. The task included trials that provided matches between stimulus and probes that occurred either between or within hemi-fields. The response required was a go/no-go decision in which the participant stated whether a match was present between any of the stimulus letters and the probe. Task demand was manipulated by matching letter based on either their physical similarity (e.g. ‘A’ & ‘A’) for low task complexity and their name (e.g. ‘A’ & ‘a’) for high task complexity. Performance on both conditions was also compared between older and younger adults. The authors found that for low levels of task demand, both older and younger participants showed an advantage for within-hemisphere processing compared to between-hemisphere processing (Figure 2.3). For high levels of task demand, similar reaction times for within and between hemisphere processing for younger participants were observed. However, older adults demonstrated a clear advantage for between-hemisphere processing for the higher task demand condition. This was manifested by a significant interaction between age group and task difficulty (F (2,80) = 3.99, p = .02). Therefore, for older adults, the cost of interhemispheric processing was negated by the benefits of greater resources. For the younger adults, resources were sufficient for all levels of task demand any advantage gained by processing across hemispheres was negated by the cost of doing so.

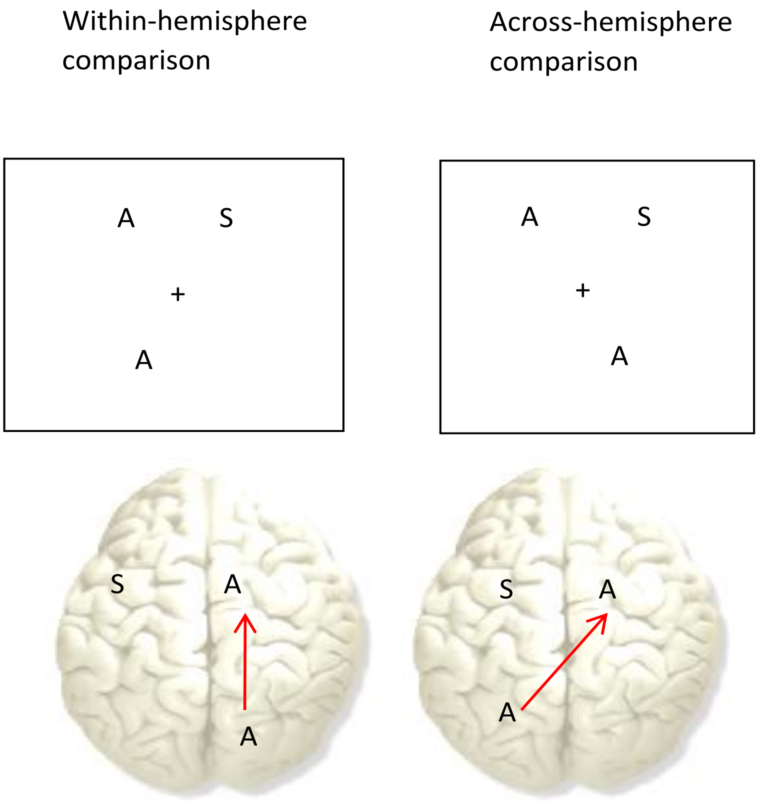

Figure 2.2: Schematic of within-hemisphere and across-hemisphere trials adapted from Reuter-Lorenz et al. (1999). Within-hemisphere matches are represented by the correct target and probe in the same hemisphere. For Between-hemisphere matches, the location of the correct match requires across hemisphere processing.

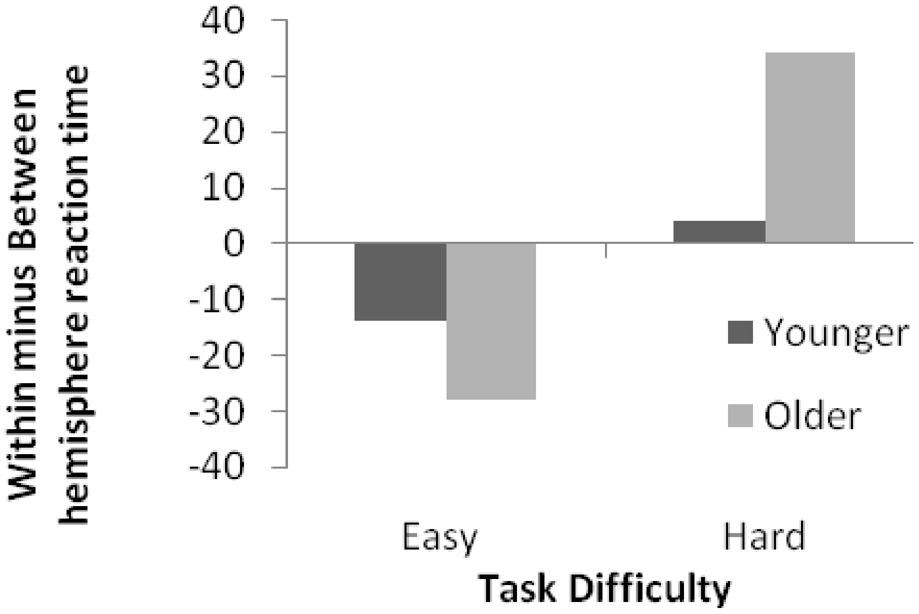

Figure 2.3: Results reported by Reuter-Lorenz et al., (1999). Note: bars represent within-hemisphere minus between-hemisphere reaction times (ms). Negative scores reflect faster within-hemisphere processing.

The same visual field paradigm was also used in a study investigating the efficiency with which the two hemispheres interact in response to age-related task demand (Cherry, Adamson, Duclos, & Hellige, 2005). Young and old participants were given a set of memory span tasks in order to relate to differences in cognitive resources to the advantage provided by hemispheric communication. As per Reuter-Lorenz (1999), the researchers found that the cost of interhemispheric communication was greater for older than for younger adults as evidenced by lower performance in the low task demand condition. Within the older group, those adults who had lower memory spans benefitted more from the higher task demand conditions being presented across the hemispheres. Therefore, further division was created between the lower resource group i.e. older adults, and within this group those with the lowest resources benefited the most. This provides further evidence for a functional contribution of the contralateral hemisphere and an on-demand view of compensation that points to a moderating mechanism to provide this service. The possible advantages of interhemispheric processing in younger adults by pushing task demand even higher are discussed in Chapter three.

In order to investigate inconsistencies in the strength of the across-hemisphere advantage (Cherry et al., 2010), Guzzetti and Daini (2014) proposed that cognitive reserve was the moderating variable between age and task demand. In a further replication of the study by Reuter-Lorenz et al. (1999), the researchers used years of education as a proxy for cognitive reserve. As before, findings demonstrated an advantage for within-hemisphere presentation of stimulus and probe for lower demand conditions and an across-hemisphere advantage for higher demand conditions, with older participants taking advantage of interhemispheric processing at lower levels of task complexity. Further, the authors found a significant negative correlation between years of education and the size of the across hemisphere advantage ($r = -.441$, $p <.05$). They postulated that any variability within older adults with regard to recruitment of the contralateral hemisphere may be due to cognitive reserve as measured by the proxy years of education. However, this poses an additional question as to the nature of cognitive reserve as represented by this proxy. The observation that activation is increased in a completely different region in older adults clearly fits the neural compensation aspect of cognitive reserve. Whilst an advantage for across-hemisphere matches are not necessarily evidence for a buildup of cognitive reserve, they do demonstrate a pathway by which additional resources can be recruited. Continual cognitive challenge, such as would occur through high levels of education, may strengthen this pathway. However, less contralateral activation in conjunction with higher levels of education would also suggest that greater reserve gained from the continual use of networks underpinning various cognitive functions means that the need for compensatory recruitment from elsewhere is lessened.

2.1.4 Recruitment across the hemispheres

This section describes the possible reasons for recruiting resources contra-laterally when it would be rational to assume that local recruitment of resources is more economical given the cost of processing via the corpus callosum (Banich, 1998). There may be a number of possible explanations why recruitment would occur over such a distance. The most obvious of which would be the absence of local resources forcing recruitment to occur between hemispheres. However, this may be true for the PFC in both hemispheres since they are more susceptible to age as a whole (Bloss et al., 2011). An alternative suggestion is that recruitment from differing functionality may be due to the arbitrariness of the recruitment procedure, known as *nonselective recruitment* (Logan et al., 2002). If recruitment is perverted then it is entirely plausible that the appropriation of resources would occur between functions that are not computationally compatible. Greater availability of resources may present a more attractive prospect than those available locally regardless of functional similarity.

2.1.4.1 Functional specialisation of the hemispheres

Functional dissimilarity may also pose an additional cost for recruitment across hemispheres. The Hemispheric Encoding/Retrieval Asymmetry (HERA) model demonstrates the lateralisation of functionality within episodic memory (Tulving et al., 1994) . Broadly speaking, the HERA model asserts that the left prefrontal cortical regions are involved with the retrieval of information whereas the right prefrontal regions are not. Conversely, the opposite is true with regards to the right hemisphere and encoding. In the absence of specific imaging studies investigating encoding, Tulving et al. (1994) revisited a number of memory studies to demonstrate the left hemispheric specificity of this process. For example, Peterson et al (1990) studied brain activation patterns in response to the presentation of English words and non-words that obeyed English grammatical rules. The left hemispheric activation they found in response to these stimuli was additionally interpreted by Tulving as evidence for encoding. A number of imaging studies involving retrieval had already demonstrated right hemispheric specificity, including one carried out by Tulving et al investigating retrieval in the context of previously encoded versus novel sentences. Recognition of ‘older’ sentences was associated with increases in activity in the right hemisphere.

There are a couple of minutiae to Tulvings (1994) model. For example, the involvement of the right prefrontal regions is much stronger for episodic encoding than semantic encoding. However, a further review of a number of additional PET studies (Nyberg et al., 1996) has confirmed the HERA models’ basic assumptions. More recently, these assumptions have been successfully tested using high resolution ElectroEncephaloGram (EEG) methodology (Babiloni et al., 2006).

Blanchet et al., (2001) provide behavioural evidence of functional specialisation of the hemispheres using divided visual field tachistoscopy. Verbal and visual materials were used to investigate encoding and retrieval effects and presented the stimuli to the left and right visual field of each participant. Blanchet et al’s paradigm assumed that processing stimuli by a non-specialised hemisphere would be less efficient. If a recognition task requiring retrieval was presented to the right visual field and contra-laterally processed in the left hemisphere, lower accuracy would be demonstrated than if the stimuli had been presented to the left visual field which the right hemisphere is believed to process. The results were valid for long term episodic memory and short term verbal memory. Whilst episodic and verbal encoding and retrieval are only two of a number of functions carried out by the PFC in different hemispheres, the evidence provided in support of the HERA model demonstrates that the compensatory activation that occurs across hemispheres may involve functionally different regions.

2.1.4.2 Nonselective recruitment

Another reason for recruitment across hemispheres would be that recruitment is the result of a random process. Logan, Sanders, Snyder, Morris, and Buckner (2002) suggest that one of the driving forces behind this process of *nonselective* recruitment is that there may be a particular absence of more appropriate resources within closer distance. The dissociation between the recruitment of completely different networks and the under recruitment of normally recruited regions was investigated by tracking both processes in an imaging study in which participants of different age groups were given a range of encoding conditions (Logan et al., 2002). Non-selective recruitment in terms of bilateral hemispheric activation endured even when under recruitment was reversed by supportive task conditions. Non-selective recruitment was found only in participants older than 73 whereas under recruitment was already evident in participants below this age. This age difference in onset provides further evidence for the dissociation of bilateral recruitment and the under recruitment of neural resources.

One point to note is that Logan et al.'s (2002) definition of nonselectivity must be accepted with caution. They specifically define nonselective recruitment as the recruitment of brain regions not normally associated with activity in younger adults. This can be viewed as simply an alternative suggestion to the dominant theory that recruitment of brain regions not normally associated with activity in younger adults is adaptive and the result of neural reorganisation aimed at this very function. Deferring resources until they are essential is a credible alternative to the random grasp of resources that Logan et al. propose.

An alternative suggestion that would encompass both Logan et al.'s (2002) observation and the idea that recruitment in older adults is adaptive would be that the recruitment seen in older adults is a result of increased subjective task demand. Therefore, if task demand was increased to subjectively similar levels between older and younger individuals then the same brain regions would be recruited. Logan et al. provided a further interpretation of hemispheric asymmetry. They viewed bilateral activation as a random 'any port in a storm' scenario. This can be interpreted as the use of any processes, regardless of functional relationship and geographical location, if the resources are available. Even if this were so, a mechanism would still need to be available to initiate the recruitment process in the face of increased task demand. Furthermore, the positive contribution of the 'nonselectively recruited' areas has been demonstrated in studies involving TMS (Rossi et al., 2004). The application of this technique to interfere with processing in those additionally recruited regions has shown an associated drop in performance.

Frontal activation demonstrated in imaging studies which also show the HAROLD pattern may suggest that a mechanism which is triggered by task demand may be frontally mediated (Bangen et al., 2012; Cabeza, 2002; Dolcos, Rice, & Cabeza, 2002). One advantage which the PFC does have is the relative plasticity of the region (McEwen & Morrison, 2013). Such a benefit may negate the cost involved with both recruitment across hemispheres and recruitment from neural pathways underpinning dissimilar functions. It is well supported that a high level of plasticity in the PFC is necessary from a developmental perspective through the differentiation of high-level functions into more discreet processes (Kuboshima-Amemori & Sawaguchi, 2007). Therefore, the ability for functional reorganisation is already present in this region. Consquently, regardless of the relative intactness of more posterior brain regions, the ability to reorganise PFC related processes may be the more neurally viable option.

2.1.5 Neural mechanisms of recruitment between hemispheres

The following section proposes a neural mechanism that may be involved in the recruitment between hemispheres described above. The functionality of the rostral prefrontal cortex (rostral PFC) and the anterior cingulate cortex (ACC) will be described and will form the biological basis of the computational model presented in this chapter. In tasks that would normally demonstrate strong lateralised brain activation, these areas are implicated in the recruitment of contralateral brain regions to combat increased task demands.

Cognitive conflict is often associated with the presence of competing responses or processes. A classic example is the Stroop test (Stroop, 1935) in which participants are required to name the colour of a series of words denoting colours which are either printed in the colour that they denote or a different (incongruent) colour.

Longer response times for incongruent stimuli are thought to arise from the competition between the more automatic word-reading and the required colour naming (reading the word would be the prepotent response). Response conflict, such as this, elicits a robust response from the ACC (Barch, Braver, Akbudak, Conturo, & Ollinger, 2001). However, conflict can occur on a number of processing levels (Davelaar, 2008; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). The level addressed in this chapter is stimulus conflict, which occurs at the stimulus encoding level of processing when a number of stimuli are presented, only some of which are task-relevant (Bunge et al., 2002). For this study, we are focusing on stimulus conflict since it is present in the more difficult conditions of the behavioural test under consideration.

Given its involvement with those tasks which demonstrate cognitive conflict, it is a plausible suggestion that involvement of the ACC may be regarded as an index of mental effort (Botvinick, Cohen, & Carter, 2004a). Evidence for the suggestion is also come in the form of studies which demonstrate that the ACC becomes active when a task has been subjectively experienced as cognitively difficult (Paus, Koski, Caramanos, & Westbury, 1998). Poor performance in stroop tasks by schizophrenic patients has strong links to aberrant ACC activation. PET studies demonstrate underactivation in this area compared to controls while carrying out a task (Carter, Mintun, Nichols, & Cohen, 1997; Yucel et al., 2002). Furthermore, electroencephalography studies have demonstrated a lack of error related negativity as well as no relationship between conflict and activation (Alain, McNeely, He, Christensen, & West, 2002; Kerns et al., 2005). In a visual field task, the stroop stimuli were adapted to investigate hemispheric interaction (Phillips, Woodruff, & David, 1996). Schizophrenics and normal participants were presented with a colour strip and a word that was congruent, incongruent or neutral. Stimuli were presented either unilaterally or bilaterally. Unilateral presentation involved displaying all stimuli to one hemisphere. Bilateral presentation involved presenting the coloured strip to one hemisphere and the word to the other. A further condition of bilateral presentation above and below the fixation point was included by authors to control for the reaction time advantage for the presentation of a central stimulus as compared to the laterally presented one. The results of the study demonstrated a greater stroop effect in terms of longer reaction times for schizophrenic patients than controls. Moreover, interference between colour and incongruent word was reduced across hemispheres suggesting poorer facilitation across them. Difficulty in hemispheric integration was also demonstrated in the consonant-vowel-consonant (CVC) tasks when presented to both visual fields. Participants with schizophrenia demonstrated an inability to produce the higher qualitative error associated with a left hemisphere shift towards non-phonological processing (Lohr et al., 2006; Suzuki & Usher, 2009). The decreased communication between the hemispheres in both of these examples can be viewed as a result of a malfunction in the conflict detection component of the model described in this chapter. ACC failure may also be responsible for the poor performance demonstrated in patients with schizophrenia.

In healthy adults, the decline in resources that is associated with normal ageing (Raz et al., 2000) would be the reason for the recruitment of additional resources in response to increased task demand. However, Drummond, Brown, Salamat, and Gillin (2004) demonstrated that this effect can also be established by varying task demand to participants who had undergone Total Sleep Deprivation (TSD). They used a grammatical transformation task in which participants were asked whether a series of letters adhered to a rule previously provided. In this study, task difficulty was manipulated by increasing the length of the letters sequences for which the veracity was to be judged. The results of this study demonstrated a number of effects which suggest the involvement of the anterior cingulate cortex in task demand. Namely, in participants who had been subjected to TSD, increased bilateral ACC activation was evident when task demand was increased. This finding suggests that the task was still of sufficient ease to the well-rested participants. The authors also suggested an analogue between the effect of TSD on the participants and that of Alzheimer's in as much as the task elicited a compensatory response (Stern, 2002) not seen in healthy (or well rested) participants in the form of activation of bilateral brain regions not normally associated with the current task. This demonstrates both an involvement in ACC activation in monitoring task demand as part of a reactive mechanism for compensation. However, it is one that is not specific to age-related neural reorganisation.

The second biological correlate of the conflict-control mechanism refers to the part played by the rostral prefrontal cortex (rostral PFC). This region is thought to be responsible for moderating processes according to the environmental context (Benoit, 2008). Lesions to this region leaves a patient with almost intact cognitive abilities but without an ability to produce the appropriate behaviour in response to open ended situations (Burgess, 2000; Shallice & Burgess, 1991).

One of the more comprehensive accounts of rostral PFC function is the gateway hypothesis (Burgess, Dumontheil, & Gilbert, 2007), which suggests that the rostral PFC is involved in the co-ordination of stimulus-independent thought (SIT) and stimulus-orientated thought (SOT). Activation of the rostral PFC appears to increase when special attention is needed to either SIT or SOT. Studies have demonstrated that lesions to this region do not result in intellectual impairment (Shallice & Burgess, 1991; Wood & Rutterford, 2004). However, multitasking appears to be greatly affected by damage to the rostral PFC (Shallice & Burgess, 1991).

In this investigation, we will assume the function of the rostral PFC as a gateway mechanism that mediates information streams according to their task relevancy. The rostral PFC is subdivided into a medial and a lateral part. The medial part is hypothesised to direct the focus to the external world or stimulus-orientated mode, whereas activation of the lateral parts increases the focus on internal communication. For this research, the application of lateral regions is extended by assuming that activation increases communication between the hemispheres.

For the purpose of the current study, it is important to highlight that the rostral PFC has been found to be activated in studies where bilateral hemispheric activation occurred in higher performing older adults (Cabeza et al., 2002). The assumption of increased hemispheric communication does not contradict the gateway hypothesis, but rather relates the changes in activity observed to switching between SIT and SOT in response to the task demand. SIT requires greater coordination between different brain areas and therefore greater demand on a system from a greater number of sources.

Activity in both rostral PFC and the ACC feature in a number of imaging studies which have demonstrated bilateral activation. A number of the studies cited in the original HAROLD paper (Cabeza, 2002) have reported activation in at least one of the regions. For example rostral PFC activation is demonstrated along with bilateral activation in face matching (Grady, McIntosh, Horwitz, & Rapoport, 2000) and face recognition (Grady, Bernstein, Beig, & Siegenthaler, 2002) in older adults. Unfortunately, the regions of interest normally only extend to frontal cortical regions in these analyses and the ACC activation is not reported. However, Grady, McIntosh, Rajah, Beig, and Craik (1999) found bilateral activation in both young and old adults which was accompanied by bilateral activation in both brain regions BA10 and BA32. This may be due to task demand exceeding threshold for young as well as old participants.

With regards to the proposed model of neural compensation in this chapter, the rostral PFC is part of a control network which is activated when cognitive conflict is detected by a monitoring system involving the ACC. In support of this suggestion, the following meta-analysis investigates the relationship between activation in these two regions.

2.1.6 Meta-analysis of activation relationship between PFC and ACC

2.1.6.1 Method

A list of studies in which activity levels of both the rostral PFC and the ACC was taken from two meta-analysis carried out by Gilbert et al. (2006; 2010) which, in themselves, focused on the function of the rostral PFC. Of all the studies in these two analyses in which both regions were mentioned, correlations between activity levels of the rostral PFC and ACC were examined. The first meta-analysis (Gilbert et al., 2006) used was an investigation of the function of rostral PFC in a number of studies subdivided into memory (working and episodic), and mentalising which can be interpreted as attending to internal processes. The second meta-analysis also covered rostral PFC functionality and looked at co-activation with a number of distinct regions external to the rostral prefrontal cortex (Gilbert et al., 2010). From these analyses, the association in activation strength of both rostral PFC and ACC activation was investigated where an appropriate z-score could be derived. All studies cited in both of the meta-analyses which carried this information were included in the analysis. In total 60 studies were included in the meta-analysis. Of these, 17 studies reported activation in medial regions of the rostral PFC and 43 reported lateral activation.

2.1.1.1 *Results*

In most cases the activation gradient was represented by Z-scores. However, in some cases T-scores were used in which the mean was represented by 50 with one standard deviation being measure as 10. These were converted to z-scores for the analysis. When studies reporting both lateral and medial activation of the rostral PFC were taken into account, the relationship between ACC and rostral PFC was significant ($r(58) = .42, p<.01$). Furthermore, when only those z-scores relating to the lateral rostral PFC were used the result was also significant ($r(41) = .42, p<.01$). A relationship between this area and the ACC was important due to the involvement of its activation in communication between hemispheres. Finally, a non-significant relationship was found between activation in medial areas of the rostral PFC and the ACC ($r(15) = .44, p = .08$). Given the reported strength of the relationship, the non-significant relationship was due to the smaller amount of studies investigating activation in both of these regions.

Whilst a universal meta-scale cannot be applied to the studies included in this analysis, a qualitative trend towards greater task difficulty was found. For example, high activation in both regions observed in Pollmann, Weidner, Müller, and von

Cramon (2000) related to a large visual load (6*6 grid) or retaining eight motor sequences (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994). Conversely, smaller perceptual loads can be observed in the lower regions of the activation plane. For example, priming in intonation judgements (Tillmann, Janata, & Bharucha, 2003), Flanker and Stroop related studies (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003) and Stimulus-Response compatibility task (Sylvester et al., 2003) each have lower levels of perceptual load and/or require less working memory.

The significant relationship between activation levels of the rostral PFC and the ACC demonstrate that they work in conjunction with one another. The model in this chapter specifies that the reason for this co-activation is that both regions work together to provide a compensatory mechanism. Preliminary investigation into the relative difficulty of the tasks in the correlational study above suggests greater activation in both regions in relation to task demand. The following simulation provided further validation for this model by producing data that can be compared to the behavioural study by Reuter-Lorenz, Stanczak, & Miller, (1999) described above.

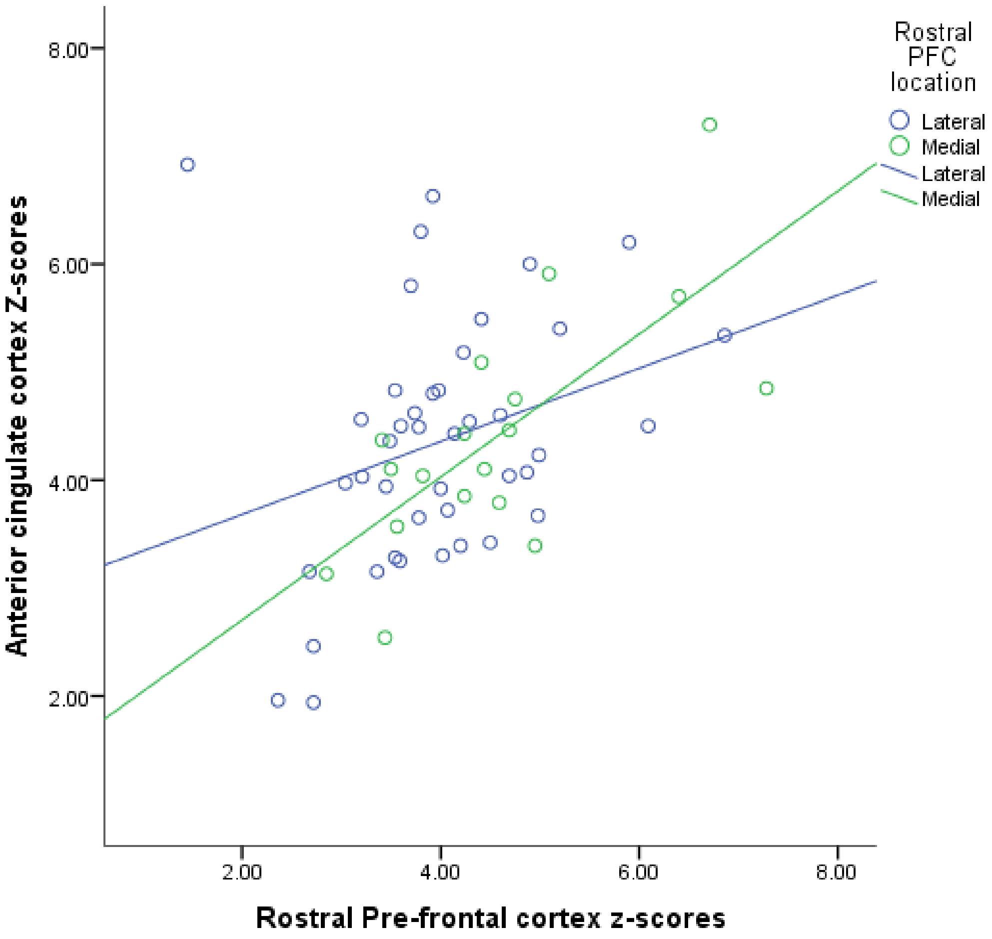

Figure 2.4: Scatterplot demonstrating Z-scores for ACC and rostral PFC activation.

2.2 The Resource Flow Model

The model is based on two testable assumptions:

1) Increased cognitive demand leads to increased cognitive conflict

2) Increased cognitive conflict is used to upregulate inter-hemispheric communication.

The first assumption requires a neural system that monitors cognitive conflict (Botvinick et al., 2004). This neural system involves the anterior cingulate cortex

(ACC) (and possibly other medial prefrontal areas). The second assumption requires a neural mechanism that influences inter-hemispheric communication. For this, we propose that in addition to the function of process flow control between internal and external events, the functionality of the rostral PFC extends to include pathway control between single and dual hemisphere processing. Together, these assumptions are sufficient to observe a bi-hemispheric neural network that recruits additional neural resources in the face of increased task demand. Included in the model is a simulation of age effects, as underlying the HAROLD model (Cabeza, 2002) in a task used by Reuter-Lorenz et al. (1999).

Computational models of specific rostral PFC function are not prevalent in the literature. However, computational models of the PFC in general represent this region as the seat of cognitive control. As such, the PFC enables processing to be carried out in accordance within the rules that constrain the current task being performed. For example, in a neural network model of the Stroop task (Cohen, Braver, & O'Reilly, 1996), the PFC is represented by an additional (context) layer which acts to bias lower-level information transfer, thus controlling the execution of behaviors which may be more compelling but not relevant to task completion. Models have also been produced of the PFC and its interaction with other systems. For example, the role of dopamine in the PFC as a stabiliser and/or neuromodulator in working memory processes has been investigated using neural network models (for a review see Cohen, Braver, & Brown, 2002). Furthermore, PFC interaction with the basal ganglia was represented in a related neural network model (Frank, Loughry, & O'Reilly, 2001) to demonstrate how the two subsystems can give rise to a more *selective gating* mechanism to facilitate efficient working memory updating.

Other models of the PFC have implicated the anterior cingulate cortex (ACC) in the role of conflict monitoring and feedback. This would then regulate the application of PFC-mediated cognitive control (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004b). With specific regard to divided processing between hemispheres, the majority of models have focused on the complementary aspects of differing connectivity between hemispheres (e.g. Jacobs & Kosslyn, 1994; Levitan & Reggia, 2000). As a further example, Weems & Reggia, (2004) compared three neural network models of interhemispheric communication. These were calossal relay, direct access, and cooperative hemispheres in their capabilities to specialise, given the left hemisphere advantage for word recognition and the lack of difference between hemispheres for recognition of non-words. The authors found that the model which best demonstrated specialisation of the left hemisphere for word recognition but not non-word recognition was the cooperative model. This was due to hemispheric transfer and the dynamics between the hemispheres themselves. This study provides compensation evidence for the advantages of interhemispheric communication, a property essential for neural compensation to occur.

The effect of task demand upon the hemispheres has also been explored using neural network models. The Bilateral Distribution Advantage (BDA; Stefan Pollmann, Zaidel, & von Cramon, 2003) describes the observed increase in performance when a task is presented to both hemifields compared to a single hemifield. A neural network model by Monaghan & Pollmann, (2003) explored the relationship between bilateral recruitment and task demand in the BDA. A three-layer backpropagation network was trained to carry out name and shape matching of two letters presented both unilaterally and bilaterally to the network with two adjoined hidden layers representing the hemispheres. Training itself was biased towards the amount of matches present since learning would not occur given the preponderance of non-matched items in the training set. The results demonstrated an interaction between task difficulty (as represented by task type) and presentation (either unilateral or bilateral) with the advantage being for bilateral presentation of more complex stimuli.

The model by Monaghan & Pollmann, (2003) behaved in this manner due to the easy mapping in the shape matching task which is nearly complete after two timesteps, whereas the letter matching task took more than two timesteps to complete. Simultaneously, the activation from one hemisphere is transferred to the other hemisphere from timestep two onwards. Thus, in the shape matching task, the model already responded before the activation is transferred to the ipsilateral hemisphere. Presenting the stimulus over both hemispheres will delay the process and thus a bilateral disadvantage is observed. For the letter matching task, the model required more processing time. By presenting the letters over both hemispheres, the bilateral processing started sooner leading to a BDA for complex but not simple tasks. In the simulation described in this chapter, the interest is in the *dynamic control* of the hemispheric connection in response to task demand. Thus, the aim is to provide a dynamic explanation of the *active recruitment of resources in response to task load*.

The model described here provided a qualitative account of a mechanism underlying and resulting in the observed brain reserve capacity. Due to its success in previous models, a capacity-limited activation buffer was included (Davelaar, 2007; Davelaar et al., 2005). Each item in the buffer has self-excitatory connections to enable activation after the initial presentation of the stimulus. However, lateral inhibitory connections provide competition among items. This results in capacity limitation since items drop from the buffer when too many are active at the same time (see Davelaar et al., 2005 for a full description of the capacity limited activation buffer). This model builds on previous work on the activation buffer (Davelaar, 2007; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005) and extends this by including a conflict/control loop (Davelaar, 2009).

Simply providing a mechanism with limited capacity would be inadequate without a method of monitoring when capacity is near full. Therefore, the model included a method of doing so by way of monitoring the conflict between the inhibitory projections from each of the items in the buffer. In neurological terms, this strategic adjustment is performed by frontal processes in response to increased conflict as monitored by the ACC (see Botvinick et al., 2004 for a review). In the model, the strategic adjustment is made by adjusting the weights between the hemispheres to provide greater resource. This is carried out as a direct function of the conflict. This has been successfully applied to related ideas such as producing confidence ratings (Davelaar, 2009) and stimulus conflict in the flanker task (Davelaar, 2008).

2.2.1 The task

As stated earlier (in the introduction), the task which was to be modelled was based on the visual field study by Reuter-Lorenz et al. (1999; Figure 2.2). This required participants to match letters, either by their physical properties (e.g. ‘A’ and ‘A’) or by their name (e.g. ‘A’ and ‘a’), the former being easier given that it is purely a perceptual task with the latter requiring an additional level of computation by virtue of the semantic mapping required.

2.2.2 Application to the task

The simulation represented single trials of the within-hemisphere or between-hemisphere matches under both easy and hard task conditions. The model comprises three components (see Figure 2.5 and Figure 2.6). The first component is a localist representation of each of the task inputs given letters ‘A’, ‘S’, ‘M’ & ‘G’ presented over both hemispheres with a matching probe (in this case ‘A’) presented to one hemisphere or the other. Therefore the input comprises of ten ‘nodes’, left and right representations of A-G plus a target for each hemisphere. The inputs were connected to the activation-based buffer via weighted connections between each of the local representations and each item in the buffer. The initial weights represented both strong (1.0) within-hemisphere connections and weak (0.5) between-hemisphere connections.

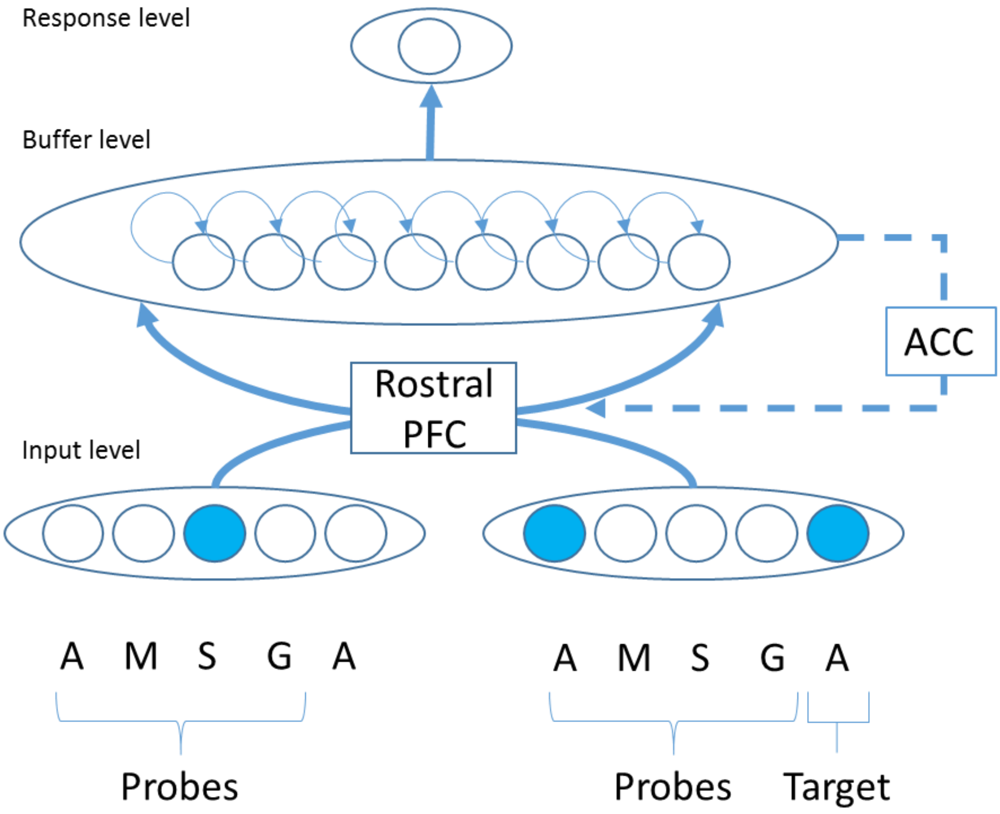

Figure 2.5: Architecture of the resource flow model. This example represents the within hemisphere match in Figure 2.2. The model consists of an input connected to the buffer via weighted connections. The rostral PFC adjusts the size (weight) of the connection bet between hemispheres according to the amount of conflict between items in the buffer monitored by the ACC. Task difficulty would be increased by activating more representations to increase perceptual load.

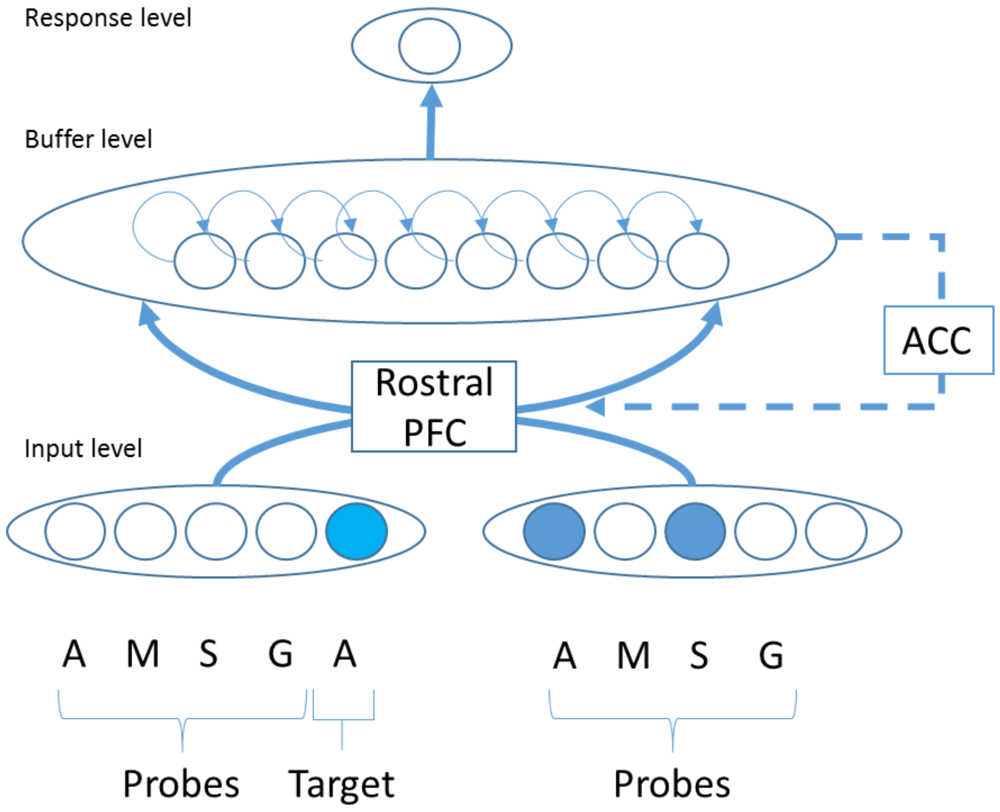

Figure 2.6: Architecture of the resource flow model. This example represents the between hemisphere match in Figure 2.2. The model consists of an input connected to the buffer via weighted connections. The rostral PFC adjusts the size (weight) of the connection between hemispheres according to the amount of conflict between items in the buffer monitored by the ACC. Task difficulty would be increased by activating more representations to increase perceptual load.

2.2.3 Implementation

A number of parameters dictate the activity level (χ) in the representation in the buffer level as well as the amount of conflict in the system. These factors are represented in Equation 1. χ_i (t + 1) is the activation of unit $_{(i)}$ at time t+1. α is the strength of the self-recurrent connection of each item in the buffer. *F* is the output activation function:

$$\frac{x}{1+x}$$

β relates to strength of the lateral inhibitory connections to the other items. λ is the Euler integration constant which relates to decay over time associated with keeping items in memory:

$$\chi_i(t+1) = \lambda\chi_i(t) + (1-\lambda)[\alpha_i F(\chi_i(t)) - \beta\sum_{j\neq i}^{N} F(\chi_j(t)) + I_i(t) + \xi_i(t)]....[1]$$

Conflict in the system is calculated by the amount of lateral inhibition between items in the buffer. N relates to the number of items in the buffer whereas I_I(t) describes the input to units $_i$ at time (t). This then informs the amount of contralateral activation in the model. It is also possible that Gaussian distributed noise (ξ) can also be introduced with standard deviation σ. However, noiseless models were produced in this investigation.

To represent both younger and older adults, α, the strength of self-connectivity of the units in the buffer was adjusted. Older adults were represented by α=1.6 and younger adults by α=2.2 (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005). To demonstrate the necessity of a conflict monitoring function in inter-hemispheric recruitment of resources, models were produced with and without this function. All other parameters remained constant throughout ($\beta = 0.2$, $\lambda = 0.98$).

2.2.4 Testing

The model ran for a total of 1000 time steps for each of four conditions. Each condition was represented by activating the input nodes relating to the both within and between for easy and difficult task demand. Therefore, the four conditions were within-easy, within-hard, between-easy and between-hard. The localist representation of each condition was then multiplied by the weight matrix containing between- and within-weights at each related position. These activation levels were the starting activity states of items in the buffer. Therefore, easy matches were represented by activation in two buffer items and hard matches were represented by activation in four items. Activation of each of the items was calculated according to Equation 1. At each time step, the weight matrix was adjusted. Since all cases in this investigation represented a match between probe and stimulus, the settled activation level of the item representing the matched probe was used as a proxy for the speed of the match response.

2.3 Results

For direct comparison to the behavioural study, activation of within hemispheres was subtracted from activation between hemispheres. Final activation data was recorded for the model both inclusive and exclusive of the conflict monitoring process (See Figures 2.7 and 2.8 respectively). Activation was used as a proxy for reaction times in that greater activity would cause a faster decision to be made. For ease of comparison the net reaction times from Reuter-Lorenz et al. (1999), are provided (see Figure 2.6).

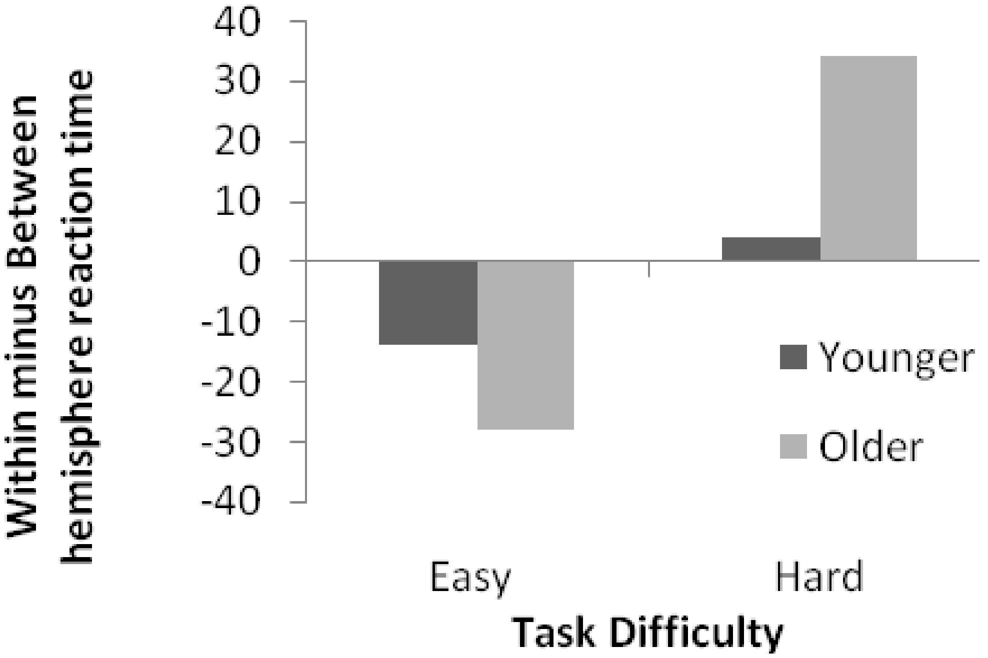

Figure 2.6. Results reported by Reuter-Lorenz et al., (1999). Note: bars represent within-hemisphere minus between-hemisphere reaction times: negative scores reflect faster within-hemisphere processing.

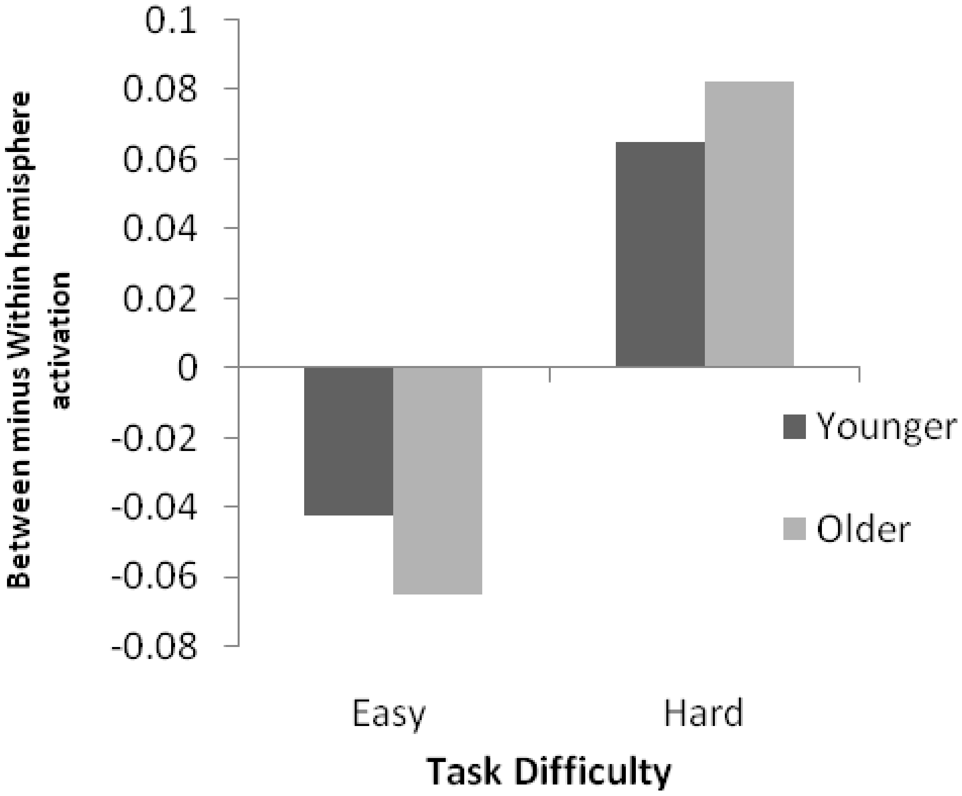

Figure 2.7. Results of model *with* conflict monitoring. The difference in hemispheric activation is used as a proxy for differences in cognitive processing as measured with reaction times.

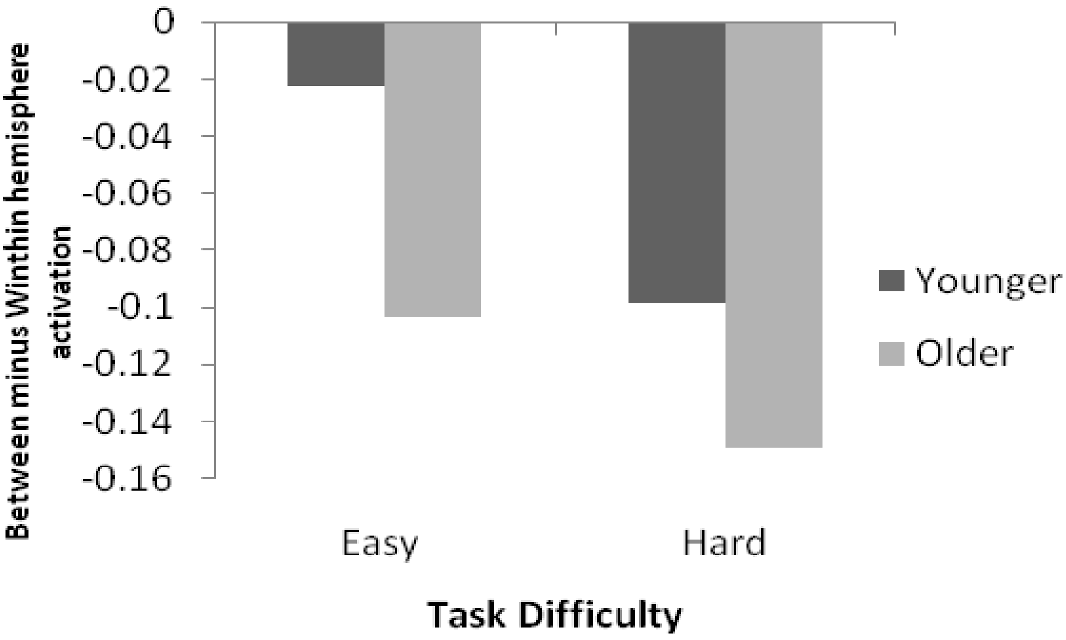

Figure 2.8. Results of model *without* conflict monitoring. The difference in hemispheric activation is used as a proxy for differences in cognitive processing as measured with reaction times.

2.4 Discussion

This chapter has presented a mechanistic account of neural compensation through increased hemispheric communication. The trigger for this effect is increased task demand. Justification for the realisation of the model has been described in detail above in terms of the HAROLD model (Cabeza, 2002) and subsequent studies that have demonstrated that the additional activation in the contralateral hemisphere supports the neurological decline observed in the hemisphere normally associated with the processes in question (Manenti, Cotelli, & Miniussi, 2011; Rossi et al., 2004). In particular, the model was specifically designed to reproduce the experimental procedure associated with a visual field study in which presenting a difficult task across hemispheres in older adults increases performance compared to presenting the task within hemispheres (Reuter-Lorenz et al., 1999).

Necessity of the component parts of the model is suggested by the above evidence regarding the Gateway hypothesis. Further, the involvement of two main components, the rostral PFC and the ACC are clearly defined in their contribution to the model. Clear evidence for the association between activation levels of both of these elements was demonstrated in the meta-analysis presented above. The model is also sufficient in encapsulating both concepts of load detection and opening up communication between both hemispheres with just the rostral PFC and the ACC.

The results from this study demonstrate a pattern of activation that reflects the cerebral activation observed in response to a greater cognitive load. That is, on harder tasks, the simulation representing older adults demonstrated greater between hemisphere activation than younger adults. Therefore, this model provides an account of the activation viewed in the HAROLD literature (Cabeza, 2002) given that greater biliateral activation was observed in older adults due to the increased subjective task difficulty. Furthermore, when increased activation was viewed as a proxy for decreased reaction time, the pattern of response times for within-hemisphere and between-hemisphere over easy and hard task conditions is similar to that of the behavioural study carried out by Reuter-Lorenz et al. (1999). These results provide us with a picture of the processes involved in the bilateral recruitment of resources in the face of increased task demand.

The model presented in this chapter presents a picture of recruitment when task demand is subjectively high enough to initiate this process. What this model also represents is a controlled method of recruitment of resources across hemispheres. This process suggests that this facility is not simply the result of random breakdown of neural resources but is a faculty which has been in place throughout life span. Such a proposition would be in line with CRUNCH model (Reuter-Lorenz & Cappell, 2008) which sees the recruitment of additional resources as age-invariant. Differences between older and younger participants arise in imaging studies due to the subjective level of difficulty. A capacity for recruitment which occurs in both younger and older adults would suggest that the additional activation is therefore not due to dedifferention of functionality. Furthermore, the involvement of the rostral PFC as a mechanism for switching between within and between hemisphere processing would suggest that recruitment is selective and not the result of a random grab, as suggested by non-selective recruitment (Logan et al., 2002). However, the specificity of the area in the contralateral hemisphere remains to be seen.

The necessity of the adjustment of level of self-excitation of each of the nodes in the capacity limited buffer supports a view of declining dopamine and its function as a neuromodulator in old age (S.-C. Li et al., 2001). In manipulating α as a reflection of the strength of the self-connectivity of the units, the model was able to replicate the pattern observed in the behavioural study by Reuter-Lorenz et al. (1999). The success of this model also supports previous modelling attempts which have successfully represented the effects of catecholamines as neuromodulators (e.g. Cohen & Servan-Schreiber, 1992; Usher & Davelaar, 2002).

One of the assumptions of this model not previously discussed is the flexibility of the donor hemisphere, that is to say the hemisphere that does not normally undertake the processing of a particular function. When relating this to the HERA, the question arises of the ability of one hemisphere which was normally contributing to a different function to be able to economically add additional processing power. Therefore, not only may a cost be applied in terms of communicating via the corpus callosum but also in terms of the plasticity of the donor function. Characterising how two different functions are implemented works at the cognitive level but attempting to describe them as similar or different at the hardware level would provide more of a challenge. One possible way this could be explored is through developing modular neural networks to carry out two distinct functions (Jacobs, Jordan, & Barto, 1991) and comparing compensation between distinctive versus similar functionality.

Whilst the model was presented as proof of concept of demand-based recruitment, the qualitative fit to the data allows us to make some tentative predictions. Primarily, these involve the pattern of data in response to varying levels of task demand beyond those investigated in this study. Although only two levels of task demand from the behavioural study have been used, the trend for faster reaction time across hemispheres is shown for both medium and higher levels of task demand in Reuter-Lorenz et al.'s (1999) study remains the same. Therefore, increasing levels of task demand presented to the model should result in the same pattern at output. However, at a certain level of task demand it is possible that the amount of control that can be exerted reaches its maximum. Therefore, future directions should include a systematic study of the model over varying levels of task demand.

One question that has frequently risen throughout this chapter is whether or not the described mechanism is the result of neural reorganisation during ageing or simply that the additional bilateral activation observed in older adults would also occur in younger adults if task demand was high enough. The functionality of the ACC and the rPFC does not appear to change as we get older. Conflict monitoring in children is associated with ACC activation in children and younger adults (Kerns et al., 2004; Rueda, Posner, Rothbart, & Davis-Stober, 2004). Further, much of the research relating to the gateway hypothesis and the switching abilities of BA10 relates to younger adults (Burgess, Dumontheil, & Gilbert, 2007; Gilbert et al., 2006). Therefore, the only difference that may occur between older and younger adults is that which was realised by the size of the working memory buffer. This would lead to a behavioural prediction that presenting stimulus bilaterally will eventually become advantageous when the task becomes demanding enough.

The results capture the data patterns from both a behavioural study and the imaging literature. The model was applied to a simple task to highlight the strength of its conceptual underpinnings. It demonstrates that conflict monitoring can play an important part in the recruitment of neural resources. However, it may be necessary to go beyond the scope of descriptive models in order to investigate this process in more detail. The use of neural networks may provide a basis for further behavioural and neuroimaging studies. Such work could look at the effect of age-related parameter changes upon resource allocation. For example, age-related changes to the neural substrate underlying either conflict monitoring or the activation-based buffer may explain the individual differences observed when imaging human participants under differing task conditions.

Possible additions to the model might include some fine tuning of the parameters to achieve lower across hemisphere advantage in the younger model for the harder task. Furthermore, the model could be extended to include the full range of task difficulties used in the experimental study. Future models may include the production of a decision-making version of this task in which the model is trained to respond accurately to presentations of the stimulus whether or not they are presented within one hemisphere or between them. Such a model would then provide an opportunity to derive some proxy of reaction time beyond the activation-based measure used in the current study. Reaction time distributions could also be produced which would allow for investigation into any changes between conditions that occur within the latency itself. These might include stimulus perception and motor response time, the latter almost certainly reflecting some of the difference between older and younger participants in the current paradigm (Whelan, 2007).

One caveat of this study is that demand itself cannot be directly compared between that experienced by human participants and the model. However, systematic study may reveal relationships in the data common to both the model and human participants, including the expectation of a close functional relationship between the ACC and rPFC during resource allocation.

In this chapter, a model is presented of resource allocation in response to increased task demand using conflict monitoring as a trigger for cognitive control. The proposal builds on a combination of four separate literatures: activation-based working memory, conflict monitoring and control, functional significance of the rostral PFC, and neural compensation. The model suggests a plausible and testable mechanism in which contra-lateral regions are recruited in task processing when task demand increases relative to the functional capability of the function specific hemisphere.

Chapter Three: Investigating the age invariance of across hemisphere neural compensation

3.1 Introduction

This chapter describes an empirical study extending the visual field paradigm explored in the previous chapter (Guzzetti & Daini, 2014; Reuter-Lorenz et al., 1999). The purpose of doing so was to provide a level of task difficulty which would potentially elicit a compensatory response from younger adults. This was carried out to investigate the suggestion that a compensatory mechanism, such as that described in Chapter two is age invariant. That is, rather than compensation being the result of old age per se, it is more to do with the difficulty of the task as perceived by the individual (Schneider-Garces et al., 2010). Therefore, an advantage for across hemisphere processing at levels of high task demand in younger adults would support this conjecture.

Presenting a stimulus across hemispheres can provide an advantage for older adults. There are two possible explanations for this phenomenon. The first is that older adults undergo some form of neural reorganisation in order for compensation across hemispheres to be achieved (Cabeza et al., 2002; Li, Moore, Tyner, & Hu, 2009). The second suggestion relates to the idea that across hemisphere compensation is not exclusive to older adults and that the same advantage for across hemisphere presentation of stimulus would be observed if the subjective difficulty of the stimulus were increased for younger adults. Given that the brain regions involved in in the compensatory mechanism described were not particularly susceptible to normal healthy ageing, the action of the mechanisms would be the same for younger as well as older adults if task demand were sufficient. This chapter explores this question further and describes evidence pointing to this possibility. The study described in this chapter aims to increase task difficulty for younger adults beyond that employed in previous studies. With this in mind, the latter part of this introduction explores the implementation of stimulus in previous visual field studies.

3.1.1 Compensation is the result of neural reorganisation during ageing

The idea that compensation occurs as a result of ageing or age related pathology relates to compensation being an adaption of the ageing process. Therefore, something happens as we age to facilitate the recruitment of additional brain areas to underpin cognitive processing (Stern, 2002). There are two overarching themes that can be applied to this phenomenon. Firstly, it is the result of a deliberate mechanism which has evolved to come online during senescence in order to facilitate this process. Secondly, compensation is a side-effect of the biological decline which occurs over age. The following evidence explores this suggestion.

3.1.2 Biological evidence

5.1.1.1 Dopamine

One of the contributing factors towards a reduction in hemispheric asymmetry that occurs in older adults as opposed to younger adults could be a reduction in dopamine which itself is asymmetric in its distribution across hemispheres (Vernaleken et al., 2007). From an initial standpoint, studies have demonstrated that in normal healthy adults, dopamine appears to be distributed differently across the hemispheres. For example, in looking at the biological correlates for a preference for the right hand use, de la Fuente-Fernández, Kishore, Calne, Ruth, & Stoessl (2000) found asymmetries in dopamine uptake in the putamen. Participants were injected with the radiotracer fluorodopa, a radioactive version of L-dopa which itself is a precursor of dopamine. This technique allows dopamine uptake to be successfully measured using a PET scanner. The degree to which each participant was right or left-handed was measured by using the Purdue pegboard test (PPBT; Tiffin & Asher, 1948). The researchers found that the degree to which the right hand was preferred in right-handed subjects was related to an increase in dopamine uptake in the left putamen. Further, in a study in which dopaminergic receptors were counted rather than the metabolism of dopamine itself, an increase of D2 dopamine receptors was found in the right compared to the left striatum (Larisch et al., 1998). In meta-analysing the results of 15 studies investigating the prevalence of D2 receptors in the brain as a whole, the researchers predicted hemispheric asymmetries would exist. The researchers used 18 volunteers and injected them with a radioactive tracer which bound to D2 dopamine receptor sites. Using PET techniques, the researchers found a significant increase in right compared to left measures of striatal dopamine receptors.

As with the activation in hemispheres, the asymmetry in dopamine availability between two hemispheres also appears to decrease with age. From a global perspective, dopamine decreases with age (see Chapter one). Biomarkers such as those used in investigating dopamine asymmetry in healthy adults have been used to demonstrate a decline in D1 and D2 receptor densities over age (Rinne, Lönnberg, & Marjamäki, 1990; Wang et al., 1998).

The lack of a suitable radioactive ligand for areas in which dopamine is more sparse, such as the frontal lobes, has hampered research in this area (Bäckman et al., 2006). Therefore, much of the research has been focused on striatal dopamine loss over age. However, an earlier study by Suhara et al., (1991) did find a decrease in the more prevalent D1 receptor in the frontal cortex as well as decreases in the striatum over age. The researchers used ‘SCH23390’ as a radioactive ligand for D1 dopamine receptors which was introduced to 17 participants ranging in age from 20 to 72 years old. PET techniques uncovered a 39% reduction in dopamine receptors in the frontal cortex and a 35% reduction in the striatum. Furthermore, post-mortem studies have offered some indicators of receptor loss in frontal regions in D1 and the much more rarefied extra-striatal D2 receptors (Kaasinen et al., 2002; de Keyser, De Backer, Vauquelin, & Ebinger, 1990).

As well as an overall reduction in dopamine over age, the asymmetry between hemispheres also appears to reduce with age. In a study involving 21, healthy males aged between 24 and 60 years levels of D2 and D3 availability were measured using a radioactive marker and PET techniques with the addition of a structural MRI investigation to confirm location of the binding sites (Vernaleken et al., 2007). Independent of age, the results demonstrated that D2 and D3 receptors were prevalent in the right putamen and caudate nucleus. Furthermore, this lateralisation was demonstrated to decline in age to the extent that there was a negative correlation between age and laterality in the caudate nucleus.

Such parallels between the reduction of dopamine asymmetry and the reduction in activation asymmetry (Cabeza, 2002) cannot be ignored. However, the question remains as to how such an age related decline in a neurotransmitter with several functions can lead to the offset of age related cognitive performance decline that can be observed with older adults who demonstrate relatively greater decrease in activation asymmetry (Cappell et al., 2010). One possible answer may come from the modulatory function which dopamine performs on neurons in the frontal lobe by increasing their responsivity to incoming signals. With the reduction in dopamine in specific areas, the dedifferentiation of cognitive functions occurs. Dedifferentiation was described in chapter two and relates to the collapse of distinct cognitive functions into fewer less specialised functions, initially as a way of economising for an age-related reduction in substrate (Baltes & Lindenberger, 1997; Babcock et al., 1997; Cabeza et al., 2002). This was demonstrated in a computational model in which it was shown that decreasing the gain function in a neural network increased correlations in performance across categorisation tasks (S.-C. Li & Lindenberger, 1999).

Biological evidence underpinning dedifferentiation in terms of reduced connectivity also demonstrates this to be an asymmetrical process. Using diffusion tensor imaging (DTI) as well as functional magnetic resonance imaging (fMRI), Li et al. (2009) demonstrated asymmetrical connectivity declines during ageing. In region specific to working memory it was revealed that whilst overall connectivity decline during ageing, functional connectivity in the prefrontal-parietal region was better preserved in the left hemisphere. Conversely, DTI fibre pathways in the right hemisphere were better preserved than the left hemisphere. This evidence contributes to a picture of asymmetric age-related neurochemical and structural changes which could support dedifferentiation and therefore more accessible functionality.

Decreasing specialisation in one hemisphere in relation to the other may provide the catalyst for the spread observed in a single direction. In this sense, the benefit derived from such dedifferentiation is that it is preferential for smaller areas or functions to be carrying out tasks if there are the resources to do so but given a generalised decline, the effective regrouping of resources is the most efficient way of dealing with this. Within the hemisphere such dedifferentiation would represent an overall decline in resources and lower performance with tasks attributed to that region. However, from a between hemisphere perspective, the across hemisphere access to a less specialised albeit less efficient additional processing network may have some advantages (Park & Reuter-lorenz, 2009). In discussing dedifferentiation, Reuter Lorenz et al. (1999) states that "neural recruitment may promote dedifferentiation". However, it is likely that the reverse is also true and dedifferentiation may lead to neural recruitment.

5.1.1.2 Corpus Callosum

In a visual field paradigm, such as the one described in Chapter two as the source of behavioural data, matches across hemispheres must be mediated by the corpus callosum (Reuter-Lorenz et al., 1999). The Corpus Callosum (CC) is a bundle of nerve fibres, primarily myelinated axons which connects the left and right hemispheres of the brain. In terms of geography, the density and diameter of the 250 to 300 million axons which traverse the corpus callosum changes dramatically depending on region (Prendergast et al., 2015). Connectivity between the two hemispheres is geographically mapped to the CC with the genu or anterior third of the CC connecting the prefrontal cortices.

When information is sent to each of the hemispheres separately by segregating the two visual fields, any perceived matches between the two sets of information are the result of communication between hemispheres. In non-visual field paradigms where an individual has demonstrated activation in a contralateral hemisphere for the purposes of neural compensation (Cabeza et al., 2002), the corpus callosum must be involved. This may extend to facilitating the compensation or simply as the conduit between regions. What follows is a discussion of how age-related changes may increase this involvement to the extent where it was not available to younger adults.

In order to accommodate the CC in a version of neural recruitment which does not include younger adults, changes must occur over age. The evidence suggesting that the corpus callosum shrinks with age is tentative. For example, a subsection of 21 studies specifically related to CC size and age were taken from a meta-analysis of 43 studies which investigated a number of factors which contributed to corpus callosum size (Driesen & Raz, 1995). Effect sizes for the relationship between CC size and age were small and given an issue with homogeneity of variance in the studies, the researchers could only tentatively conclude that the CC could shrink with age. Further, more recent studies have only found small effects for volumetric change in the CC compared to cortical and allocortical grey matter (Sowell et al., 2007; Walhovd et al., 2011).

The small volumetric effects found in CC deterioration over age may be partially due to the global perspective that the above studies have taken. When the area of the CC which relates to traffic between frontal regions of the cortices is specifically investigated with techniques which highlight their connectivity, a different picture emerges. For example, 28 males took part in an imaging study which implemented a technique which allowed segmentation of specific tracts within the CC from diffusion magnetic resonance imaging (dMRI) data (Bastin et al., 2008). This meant that a clear comparison between individuals could be made of volumes of separate regions of the CC such as the genu and splenium as well as the ability to determine the connectivity of the regions to the individual hemispheres. Using this technique, the authors found a negative correlation between age and fractional anisotropy (FA), a metric of neural connectivity, in the corpus callosum. This particular correlation was specific to the genu region of the CC. Therefore, decline may be due to a reduction in connectivity rather than overall volume.

Diffusion tensor imaging (DTI) provides another method by which the connectivity of the CC can be gauged. This technique was applied to the genu of the CC in an age-related study (Gong, Wong, Chan, Leung, & Chu, 2014). Fifty-eight healthy participants took part in a whole brain analysis which included the genu and splenium of the CC as a region of interest. In general, greater degeneration was found in anterior regions than posterior regions. Axonal loss was attributed to the general degeneration with demyelination appearing to be the greater driver for anterior degeneration. Further, age related decline in FA and also mean diffusivity (MD), a further metric of white matter tract changes, were found in the genu. Significant differences in this decline compared to anterior portions of the corpus callosum were also found. Given the connections of the CC with the frontal hemispheres, such a reduction of connectivity within the genu may indicate a reduction of cross-hemisphere influence.

The corpus callosum (CC) is a broad, flat band of white matter tract that measures about 10 cm in length. Its function is to connect the left and right hemisphere.

Evidence exists supporting both an excitatory and inhibitory action on the contralateral hemisphere with some suggestion that its influence can be both (Bloom & Hynd, 2005). Transcollasal Inhibition (TCI) occurs when excitatory callosal fibres from the CC target inhibitory interneurons in a homotopic area of the contralateral hemisphere (Schutter & Harmon-Jones, 2013). The nature of TCI means that as the CC declines during senescence its inhibitory influence also declines across hemispheres leading to an activation increase in one or both hemispheres. Age-related decline in white matter tract connectivity in the CC leads to an increased level of activation in the contralateral hemisphere as it becomes increasingly less inhibited by the other one (Persson et al., 2006). Modelling evidence also supports this assertion. A neural network was produced which comprised of two cortical regions connected by an inhibitory ‘corpus callosum’ (Levitan & Reggia, 2000). Lesions to one of the cortical regions caused a large increase in activation in the other cortical region. In animal studies, severing of the corpus callosum has led to a reduction of the capability of one hemisphere to inhibit the other. For example, muricide or the phenomena of mice killing by rats is known to be lateralised in the right hemisphere and it was hypothesised that the left hemisphere moderated this behaviour by inhibiting the right (Denenberg, Gall, Berrebi, & Yutzey, 1986). In severing the connection between both hemispheres, it was found that muricide significantly increased in comparison to control animals. This demonstrates an inhibitory influence, via the CC, of one hemisphere on the other. Chiarello & Maxfield (1996) suggest that there are three forms of interhemispheric inhibition which make up functioning of the CC. Interhemispheric suppression inhibits the dynamic interaction between hemispheres to facilitate hemispheric dominance. Interhemispheric isolation relates to a decoupling of the hemispheres from the functional perspective, allowing the hemispheres to process independently. Finally, interhemispheric interference relates to the transfer of conflicting information from one hemisphere to another in order to restrict processing of the receiving hemisphere. From a cognitive perspective, DTI techniques have also demonstrated a correlation between FA in anterior portions of the CC, including the genu, and performance in inhibitory tasks (Treit, Chen, Rasmussen, & Beaulieu, 2014). This evidence supports the assertion that there is decline in the inhibitory functionality of the CC over ageing. If the inhibitory influence of one hemisphere over the other declines then it is plausible to suggest that this may increase the contribution that both hemispheres can make to a particular task.

3.1.3 Strategy change

One indirect way in which ageing could be responsible for performance-related contralateral activation can be found at a different level of description, the cognitive level (Reuter-Lorenz & Cappell, 2008). Crystallised knowledge, such as that gained through life experience is retained as we get older. Therefore, changing strategy to perform a particular task given what might be termed ‘wisdom’ is a feasible proposal. Evidence for cognitive strategy change in older adults is abundant and can be summed up as the speed accuracy trade-off in which older adults will adopt a more conservative strategy timewise when performing tasks which leads to higher accuracy (Fitts, 1954). The evidence for such a phenomenon in terms of task performance only is abundant (e.g. Baron & Mattila, 1989; Salthouse & Somberg, 1982; Salthouse, 1979). Furthermore, Lindenberger and Mayr (2014) summarised a variety of evidence which points to the greater reliance of older adults on perceptual cues than younger adults and that older adults are more likely to be drawn to cues with greater perceptual salience. Therefore, strategy change in this case relates to a greater reliance on environmental cues. This appears to be fixed in some way since older adults will still rely on external cues even if this affects task performance in a negative fashion.

Whilst it is clear that strategy change does occur, what is not so clear is the evidence relating strategy change to additional brain activation. The work of Elfgren and Risberg (1998) has already been described in Chapter one in relation to a significant increase in Cerebral Blood Flow (CBF) in relation to the utilisation of a verbal strategy in a non-verbal fluency task. However, participants were younger adults and the strategies undertaken appeared to be the result of conscious decision. This is unlike the work examined by Lindenberger and Mayr (2014) in which older adults undertook a particular strategy even if task performance suffered. Furthermore, in a weather prediction task which explicitly permitted strategy analysis, age-related activation differences were found between older and younger adults with a positive relationship between levels of activation and task performance in the latter group (Fera et al., 2005). However, no change in the strategy used was found between the two age groups. Therefore, whilst strategy change does exist and certainly demonstrates compensation of one kind it is unclear whether this type of compensation which is undertaken by older adults is the sort which can be considered exclusive to this group or whether it even relates to the contralateral activation found in higher performers.

3.1.4 Younger brains working harder?

An alternative explanation to overactivation in older adults being the preserve of older adults is that, quite simply, the same overactivation would be observed in younger adults if they experienced a subjectively similar task demand. For whatever reason, older adults experience neurological decline which affects their ability to perform as well as younger adults. Therefore, task demand is already subjectively higher and there is a need to recruit additional resources from elsewhere. Matching task demand between older and younger adults would result in the same patterns of contralateral neural recruitment. This prediction is characterised by the compensation related utilisation of neural circuits hypothesis (CRUNCH; Reuter-lorenz & Cappell, 2008). The source of neurological decline has been discussed extensively in Chapter one. Further, the neurobiological decline associated with both dopamine degradation, in the form of increased neural noise (Bäckman, Lindenberger, Li, & Nyberg, 2010), described in the previous section could also contribute to an overall decline in processing power.

The evidence in the previous section supported compensation as a result of the loosening of inhibitory influence of the CC due to age-related decline. However, the mechanism behind any compensatory function this may carry out is unclear. Further, an association between some metric of the anterior CC together with increased contralateral activation and increased task performance is missing. What studies have demonstrated, however, is a relationship between memory performance and anterior CC measures in healthy adults demonstrating that inhibition is necessary for task performance (Persson et al., 2006; Sullivan & Pfefferbaum, 2007). Further, any benefit gained by overactivation due to age-related decline, be it dopaminergic or via

CC degradation, would be mitigated by some cost within the additionally active hemisphere. No evidence suggests that neural reorganisation during age would produce a system dedicated to compensation. Any compensation that would arise due to age-related decline would be accidental and almost certainly partial (Duverne et al., 2009). Therefore, the evidence suggests that an innate mechanism exists prior to age related decline and is one that is activated by task demand, rather than ageing per se.

Bilateral recruitment in circumstances not directly related to ageing suggests that this is not an age-specific phenomena. Honda et al., (1997) examined two patients who had experienced strokes in an imaging study. Readings of CBF were taken in response to movement of the unaffected hand, movement of the recovered hand, and at rest. The researchers found that additional activation in the motor cortex of the healthy hemisphere corresponded to movement in the hand which was normally under the influence of the damaged hemisphere. The researchers concluded that compensation was occurring between healthy and the damaged hemisphere although the mechanisms involved were unknown. Whilst the ages of these two patients (60 and 75) confound the assertion that compensation is not strictly due to age-related decline, this study does show that compensation can occur under different circumstances. The same type of investigation but with a lower age range of participants (44-75, mean age 54) demonstrated a similar effect (Small, 2002). This time MRI imaging was used together with electromyography EMG, the latter used to control for mirror movements. The researchers found that motor recovery from stroke correlated significantly with CBF in the healthy hemisphere. Furthermore, animal studies using adult but not older squirrel monkeys have demonstrated this mechanism is not exclusive to ageing mammals (Nudo, Wise, SiFuentes, & Milliken, 1996). The study demonstrated that increased activation in an undamaged hemisphere, following specific damage to motor regions, was related to behavioural recovery.

3.1.5 CRUNCH

Reuter-Lorenz and Cappell (2008) propose that in order for older adults to maintain a level of task performance that is similar to the younger peers, they engage additional neural resources. However, the authors also propose that this mechanism can also be engaged by younger adults at subjectively higher task demand. This was demonstrated in a study by Schneider-Garces et al. (2010) using the Sternberg memory task (Sternberg, 1966) which allows for the parametric variation of memory load. Brain activation was then related to each individual in terms of their individual performances. This study found that when individual memory span was controlled for, differences in activation were much smaller. This suggests that the increased activation observed in older adults is the result of a more limited processing capacity rather than a systematic difference in activation profiles between older and younger adults. These results suggest that recruitment of brain regions is related to demand for additional resources rather than just an inevitable consequence of ageing.

Support for an age-invariant, processing capacity view of interhemispheric compensation is shown when older and younger adults are compared on the same task. For example (Cappell et al., 2010), used a working memory task in which participants in two groups, young (mean age = 20.8) and senior (mean age = 68.4), had to state whether or not a probe consonant had belonged to a previously presented set of target letters. The researchers used target letters presented in blocks of four, five and seven to represent increasing working memory load. fMRI analysis was used to study CBF in the brain regions involved. Age-related over-activation was found in the senior group at lower task loads than younger adults. As task demand increased further, older adults demonstrated a lower amount of over-activation. This was thought that this represented the point at which task demand exceeded all available resources for the older adults and a collapse in processing occurred. Furthermore, at these higher task loads, younger adults demonstrated a similar pattern of overactivation in the dorsolateral prefrontal cortex (DLPFC) as the older group did at lower loads. These results also support a previous study by (V. S. Mattay et al., 2006) who used an N-Back task with groups of younger and older adults. Comparable performance at the easiest level (1-back) was accompanied by bilateral activation in the DLPFC. Older adults in this study also demonstrated a point of processing collapse at which task demand exceeded all available resources and a drop in bilateral activation occurred. Interestingly, younger adults also demonstrated a similar performance and bilateral activation drop at higher loads (3-back). This study demonstrates that both older and younger adults show similar characteristics in their activation profiles in relation to subjective load.

Imaging techniques newer than classic PET and MRI scanning have also been used to demonstrate bilateral activation in the face of increased task demands in younger adults. Functional near infrared spectroscopy fNIRS is a technique in which brain activity is measured using the haemodynamic response or blood saturation levels associated with neuronal behaviour. It can also be used in the more naturalistic situation since the participant is not required to lie down. Helton et al., (2010) used this technique with fifty-seven mixed sex participants (mean age = 20) in a vigilance task in which participants were required to respond to a signal letter from randomly presented three letter stimuli. High and low task demands were built into the paradigms with a control condition in which participants simply viewed the stimuli. At lower task demand, cerebral oxygenation was lateralised in the right hemisphere. Higher task demand, however, produced a pattern of reduced lateralisation across the hemispheres. One of the limitations of this study was that the authors were unable unpick the cognitive functions attributable to vigilance. However, regional oxygen saturation scores were higher in both experimental conditions than the control. Therefore, if the need for increased vigilance can be related to higher cognitive demand in the younger participants, this study demonstrates further validation for the idea that interhemispheric compensation is a result of task demand and not ageing alone.

3.1.6 STAC

The evidence presented in this section shows that an age-invariant mechanism may exist that provides compensation when subjective task demand exceeds resources in the hemisphere normally attributed to the function. The scaffolding theory of aging and cognition (STAC; Park & Reuter-lorenz, 2009) views the additional activation observed in older adults as compensatory and a form of scaffolding or ‘shoring up’ of cognitive processes in response to challenge. In the case of younger adults that challenge may be task demand (Cappell et al., 2010) and with older adults, that challenge is age-related neurobiological decline. However, the STAC is a general theory and compensatory scaffolding, as it is known, is also augmented by environmental processes which occur over the lifespan such as exercise, cognitive training and new learning, these are known under the umbrella term of neural resource enrichment in a later iteration of the STAC theory (STAC-R; Reuter-Lorenz & Park, 2014).

The direct mechanism by which cognitive training in any form would increase accessibility to contralateral hemisphere activation is unclear. However, the effect of a stimulating environment has included neuronal level improvements such as increased brain derived neurotrophic factor (BDNF; Mattson, Maudsley, & Martin, 2004) and cortical remapping (Zhou & Merzenich, 2007), two factors which could at least contribute to the maintenance of such functionality.

Whilst environmental contributions can provide support to hemispheric asymmetry reduction, the downside is that this is usually accompanied with being older. The idea that scaffolding occurs in both young and old means that the STAC theory supports a view of age invariance of contralateral activation as a compensation mechanism. However, due to a reduced level of plasticity in older adults (Burke & Barnes, 2006), scaffolding may be far less efficient in older adults. Furthermore, younger adults that demonstrate a higher level of scaffolding may be at risk of poorer performance and accelerated ageing (Park & Reuter-lorenz, 2009).

3.1.7 Behavioural study of the hemispheres

The across hemisphere paradigm explores bilateral processing by presenting the relevant stimulus tachiscopically across the hemispheres and compared with a stimulus presented to a single hemisphere. The necessity for using both within and between hemisphere trials is to isolate an effect which is reserved for interhemispheric processing by observing an interaction with some other factor (Banich & Shenker, 1994). In the case of this study, the other factor was task demand. A number of different stimuli have been used within this paradigm in order to investigate hemispheric interaction. This section describes the use of the visual field study in interhemispheric research as well as the application of the different stimulus sets used.

An early use of a visual field paradigm was by Dimond and Beaumont (1971) in which participants were presented with digits either to the left or right visual hemifield represented by two separate screens or across both of the screens (bilateral presentation). Performance results indicated that there was a significant difference between left and right unilateral presentations and that bilateral presentation maximised performance. This was subsequently followed up by a similar paradigm in which nonverbal stimuli were used instead of digits (Dimond & Beaumont, 1972). One of the more simplified explanations of this effect was that presenting the stimulus to two hemispheres rather than one may produce a performance increase due to the 'split load' between them.

Subsequent investigations of bilateral processing have used perceptual matching tasks similar to the original study by Dimond and Beaumont (1971). For example, Norman, Jeeves, Milne, and Ludwig (1992) studied the bilateral advantage in the context of matching dot patterns in a yes/no decision task. What makes this study stand out is its inclusion of task demand as the amount of dots in each pattern increased from two to four and then six dots in each pattern. Patterns were then either presented together to the Left Visual Field (LVF), the Right Visual Field (RVF) or bilaterally in which one pattern was presented to each visual field. Overall, participants demonstrated lower errors and a faster response time when stimulus was presented bilaterally. However, these findings came with some caveats. When analysed separately, the bilateral advantage was only significant relative to RVF presentation with increasing task difficulty. Furthermore, for no-go stimuli, the bilateral advantage did not increase as task difficulty increased. Therefore, hemispheric specialisation may account for the relative differences between each of the hemispheres and bilateral presentation. However, these results do not explain the role of communication between hemispheres since a co-operative model of hemispheric interaction would manifest itself in a bilateral advantage compared to both unilateral conditions.

3.1.8 Task difficulty through computational steps

The perceived computational difference between matching items according to their shape and matching them according to semantics has been exploited in studies which have demonstrated that such a difference may interact with bilateral processing. In the first of a series of experiments, Banich and Belger (1990) used a letter matching task in which participants were required to decide whether two probe letters presented with a target which matched one of the probes in either in the same hemifield or across the hemifields. In this study, task difficulty was not manipulated by increasing the perceptual load but by varying the difficulty of the decision process. To this end, participants were required to match letters. In the easy condition, the physical identity task, participants just had to decide whether or not two of the three stimulus were physically identical. In the name identity task, an additional computational step was added by asking participants to match letters based on their name rather than physical appearance. This meant that, for example, the letters ‘A’ and ‘a’ would constitute a match. In these trials, the participant had to go beyond simple perceptual matching to make a semantic judgement. In this study, a bilateral advantage was found for the more computationally complex of the two tasks, name matching. For the physical identity condition, performance was hindered by presenting stimuli across the hemifields compared to within hemifield presentation. These results suggested that bilateral processing only produces an advantage when task demand is enough to justify the extra cost involved with the utilisation of two hemispheres.

In a subsequent study, Belger and Banich (1992) investigated the rank order of complexity in terms of increasing the amount of stimuli on-screen compared to manipulating the amount of computational steps required. In a paradigm similar to their previous study (Banich & Belger, 1990), participants were required to match letters either with regard to their physical characteristics or their name. However, in this study perceptual difficulty was also increased by using three levels of difficulty. The first two levels of difficulty required the physical matching of either two or four probe letters to a target. The final condition required participants to match letters based on their name identity (e.g. ‘A a’) which also had four probe letters and a single target. As with all visual field studies discussed here, matches were either within hemisphere or across hemisphere. A significant across hemisphere benefit was found for the physical matching conditions with five items (four probes plus one target) compared to within hemisphere matches. Furthermore, the name matching task, representing greater computational complexity, was performed significantly faster than the shape naming task of equal stimulus size. Therefore, a hierarchy can be established with perceptual load representing a lower task demand than computational complexity when the amount of on-screen items is matched.

The most recent incarnation of the visual field paradigm was one which has related directly to cognitive reserve and follows in the footsteps of Banich and Belger (1990) in the choice of stimulus used. Furthermore, the visual field study by Guzzetti and Daini (2014) provided a replication of the study by Reuter-Lorenz et al. (1999), described in chapter two, with the addition of a measure of educational attainment as a proxy of cognitive reserve. Participants were given a matching task which was divided over the visual fields. Unlike Reuter Lorenz et al, two levels of difficulty were included. Two probes and one target were used throughout with the first level of difficulty being represented by a physical identity task in which participants were required to match upper case letters based on physical characteristics. A higher level of difficulty was introduced by the requirement of participants to match upper and lower case letters according to their name. Similar to Reuter-Lorenz et al. the researchers found a greater across hemisphere advantage for the more complex tasks for older adults. What the researchers also found was a significant advantage for within hemifield trials as opposed to across hemifield trials in the physical naming task. This was accompanied by no difference in reaction times for between and within matches for the naming task. Further, when Guzzetti and Daini (2014) compared left and right within hemisphere matches, they found weaker laterality effects in older adults in relation to the left visual field advantage in the name identity task.

Hemispheric processing comes at cost (Jeeves & Moes, 1996), which was also suggested by the within hemisphere advantage for physical identity task (Guzzetti & Daini, 2014). This also suggests that to register a genuine advantage for across hemisphere processing a higher level of task demand is needed for the benefit to outweigh the cost. This would be manifested in a significant increase in performance between match types at the higher levels of task difficulty and an overall cross-over interaction between match type and task demand. If a bilateral advantage was led by subjective task demand and not age, an across hemisphere advantage may be found by increasing task demand beyond current limits for younger adults also.

In terms of its application to cognitive reserve in general, the study by Guzzetti and Daini (2014) adds to the study by Reuter Lorenz et al. (1999) in its demonstration that older adults with a greater level of educational attainment and therefore a greater level of cognitive reserve demonstrated a weaker across hemisphere advantage. Therefore, higher cognitive reserve relates to more efficient processing within a single hemisphere implying a reduced need for cognitive compensation.

3.1.9 The Study

The current study applies a divided visual field paradigm for the purpose of investigating the existence of an age-invariant, demand-related mechanism of interhemispheric communication. Using a mixture of established levels of task difficulty together with a novel extreme of task demand it was hoped that task demand was sufficient to prompt interhemispheric processing in a younger group of participants than has normally been demonstrated using this paradigm. The evidence presented in both the CRUNCH and STAC theories of ageing (Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010) suggests a prediction that younger adults will demonstrate an interaction between task demand and probe location. At lower levels of task demand, probe and target matches within hemisphere should manifest the faster reaction times for participants. However, at the high levels of task demand an advantage for across hemisphere presentations of matching probe and target will be demonstrated. Furthermore, this study seeks to extend the finding by Guzzetti & Daini (2014) with regards to performance differences between hemispheres by comparing the left and right within hemisphere matches for younger adults.

3.2 Method

Using a visual field paradigm similar to that used by Reuter-Lorenz et al., (1999) and Guzzetti & Daini, (2014), a group of healthy adults were presented with a letter matching task which increased in difficulty over five levels.

3.2.1 Design

This was a visual field paradigm with three independent variables. The first independent variable was task difficulty with five levels. The second independent variable was the location of the probe which matched the target. This has two levels, either ipsilateral to the target (within hemifield match) or contralateral to the target (between hemifield match). A further independent variable was included in this study to investigate any hemispheric effects, this was whether the target appeared in the left or right hemifield. This was a within participants design. Two dependent variables were initially used in this study, reaction time and accuracy. Reaction times were analysed from correct responses only. For the analysis, an efficiency score was calculated from the two dependent variables.

3.2.2 Participants

Twenty five healthy adult participants voluntarily took part in the study (20 females, 5 males). All the participants were students undertaking a psychology degree. The age range of the students was 18-40 (mean age = 25.9 years, S.D. = 7.0). All participants were right-handed. Participants took part in a study to earn course credits.

3.2.3 Materials

The stimuli used in this visual field paradigm were similar to those in the study by Norman et al., (1992). However, the current study departed from it by using the amount of dots as a level of task difficulty to manipulate the number of computational steps required to identify a match between probe and target (Reuter-Lorenz et al., 1999). As per previous iterations of the visual field paradigm, matches occurred between the target below the fixation point and one of the two probes above. Therefore, matches were either within a single hemifield or between hemifields. The experiment was realised using experimental software ("E-prime 2.0," 2012). The presentation of the stimulus on-screen followed the same configuration as the study by Reuter-Lorenz, Stanczak, et al., (1999). The criteria upon which the participants were asked to base matches and the stimulus presented represented the five levels of difficulty. The first two levels of difficulty required a perceptual level of processing with matching dots (Norman et al., 1992). Level two being more demanding than level one by virtue of the increased number of probes (Figure 3.1 & Figure 3.2). Levels three and four used a further level of computational complexity by including the requirement to make a semantic match regarding the number represented by dot probes and a number target. Perceptual load was also increased by adding further probes (Figure 3.3 &

Figure 3.4). The final level of difficulty (Figure 3.5) was a novel approach developed here based on the amount of computational steps required to make the match. The final and hardest level of difficulty required the participant to make a match according to whether the left or right probe and the Arabic target summated to an even number (Figure 3.5 & Figure 3.6). In trials relating to levels of difficulty which included two probes and one target (one, three, and five), the probes appeared 1.4° up and 2.8° left and right from the fixation cross. In trials relating to levels of difficulty which included four probes and one target (two and four), the probes were arranged in a 2 x 2 grid. Each row of the grid was 1.9° and 0.9° above the fixation point with each individual probe appearing 2.8° to the left and right. In all cases, the target letter appeared 1.4° to the left of the fixation cross and the same visual angle below it. The rank order of difficulty is illustrated in Figure 3.6 and

Figure 3.7. Thirty two examples of within hemisphere left and right stimuli, across from right to left and left to right, and no matches with the target on the left and right were presented in random order for each level of difficulty. This meant that the participant saw a total of 192 trials for each level of difficulty. These were randomised at each presentation. The order of the levels of difficulty was also randomised for each participant.

The letters ‘v’, ‘b’, and ‘n’ were used on the computer keyboard to respond to the type of match. Letters ‘v’ and ‘n’ were used to respond according to whether the matching probe was on the left (‘v’) or right (‘n’). The letter ‘b’ was used as the response for no match.

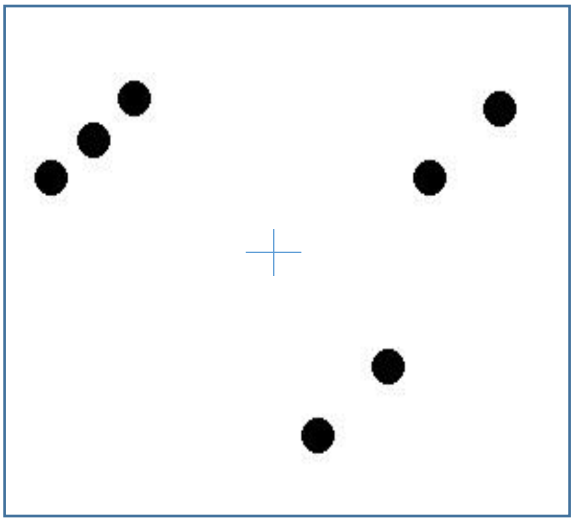

Figure 3.1: Example of stimulus from first level of difficulty. Current example demonstrates a within hemisphere match within the right hemifield. In this example, the correct response would be ‘n’.

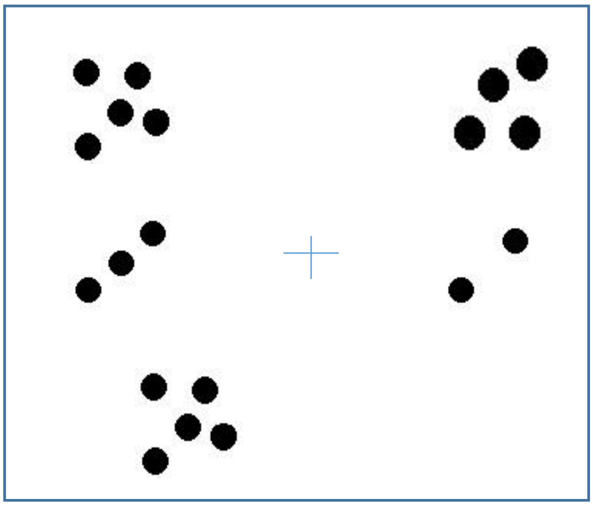

Figure 3.2 Example of stimulus from second level of difficulty. Current example demonstrates a within hemisphere match within the left hemifield with more distractor stimuli. In this example, the correct response would be ‘v’.

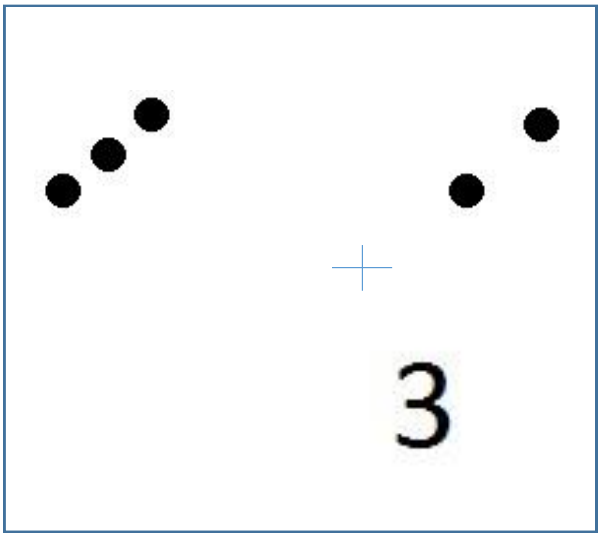

Figure 3.3 Example of stimulus from third level of difficulty. Participants were required to translate the number representations to match target and correct code. Current example demonstrates a between hemisphere match between left hemifield probe and right hemifield target. Therefore, correct response would be ‘v’.

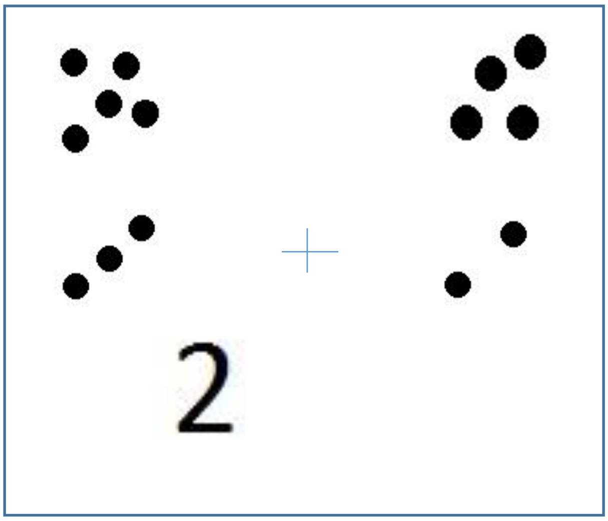

Figure 3.4: Example of stimulus from fourth level of difficulty. As per previous example but with more distractor probes. Matching probe on the right means that the correct response would be ‘n’.

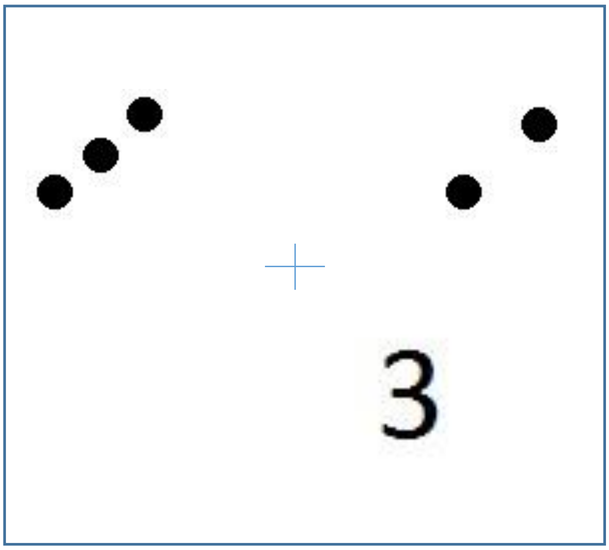

Figure 3.5: Example of stimulus from fifth level of difficulty. Current example demonstrates a between hemisphere match since the Arabic ‘3’ and the dot representation of three sum to an even number. Therefore the correct response would be ‘v’.

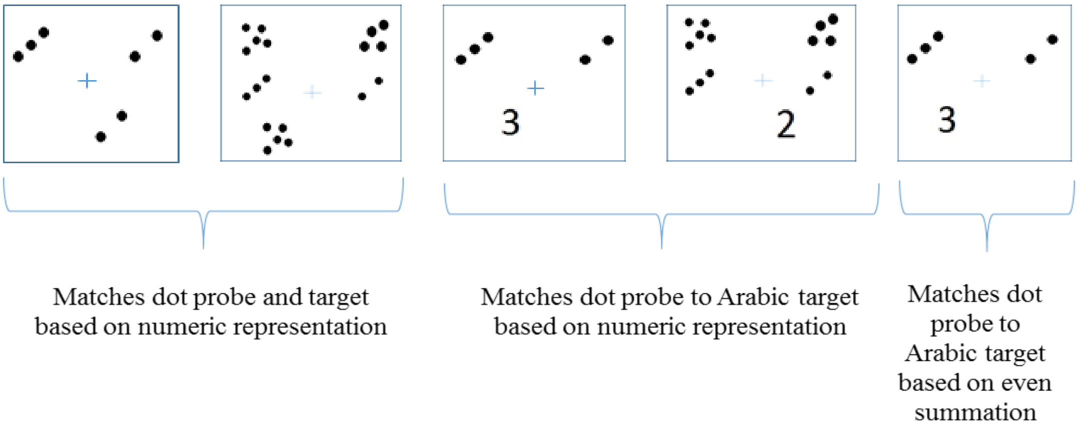

Figure 3.6: Summary of examples of within hemisphere match stimuli. Rank ordering of difficulty assumed to go from left to right.

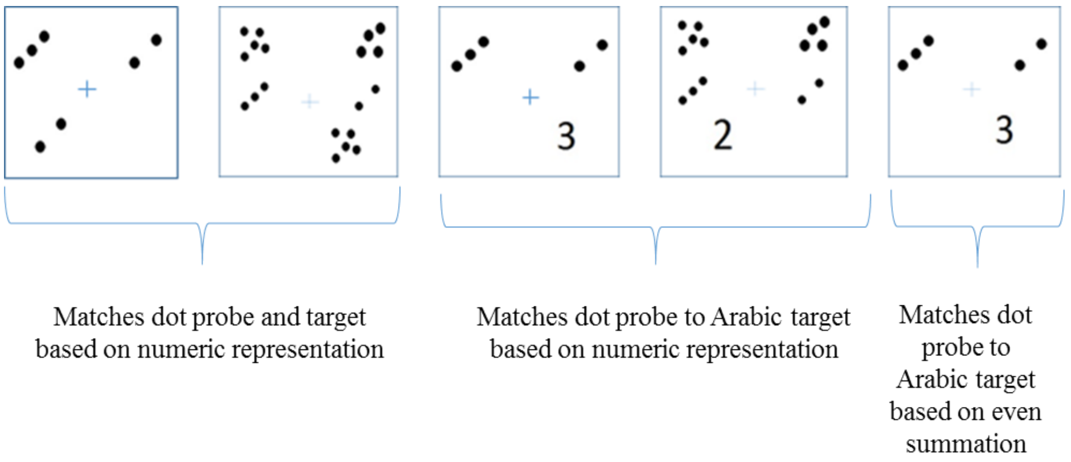

Figure 3.7: Summary of examples of between hemisphere match stimuli. Rank ordering of difficulty assumed to go from left to right.

3.2.4 Procedure

Upon meeting the participant, a written brief was provided to them explaining their rights as a participant, what they were required to do in this study, and the time it took. After informed consent was given by the participant, the participant was led to an experimental cubicle within which was a PC running the experiment. Prior to displaying any stimulus, the software asked participants for age, gender, and handedness. Participants were given written and visual instructions on what they were expected to do prior to undertaking each level of difficulty (see Figure 3.8 - Figure 3.12) and given the opportunity to practice a sample block of each of the different levels of task difficulty prior to testing. If the participant wished, they could choose to repeat the practice block. Upon proceeding, the participant was presented with a fixation cross on a blank screen for 500 ms. Following this, the stimulus was presented for 200 ms (Figure 3.13). The presentation was brief in order to avoid saccadic eye movements. Following the stimulus presentation, a response window of

1800 ms was provided for the participant to decide whether the target pattern below the cross matched a figure above the cross on the left or right side or that there was no match. If the participants did not respond within this time period, an incorrect response was registered.

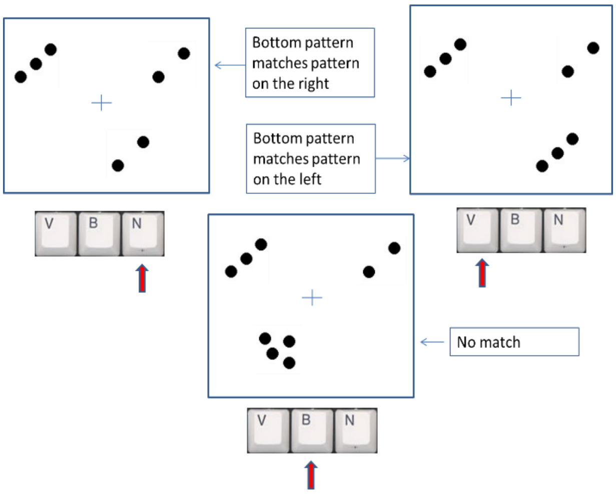

Figure 3.8: Visual instructions for participants present prior to completing first difficulty level.

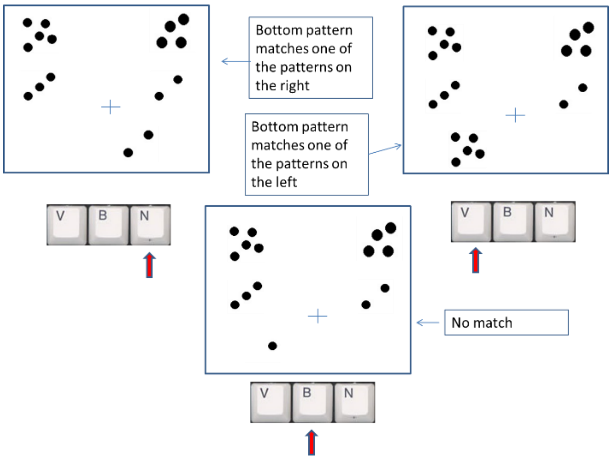

Figure 3.9: Visual instructions for participants present prior to completing second difficulty level.

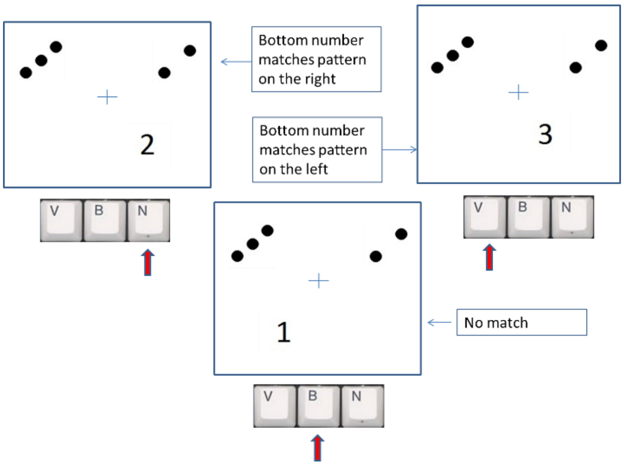

Figure 3.10: Visual instructions for participants present prior to completing third difficulty level.

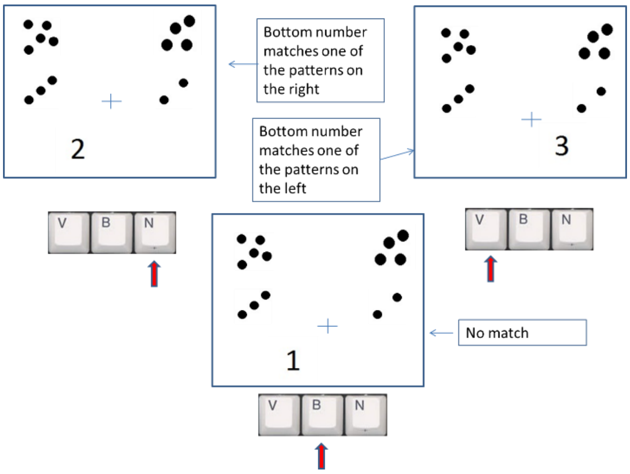

Figure 3.11: Visual instructions for participants present prior to completing fouth difficulty level.

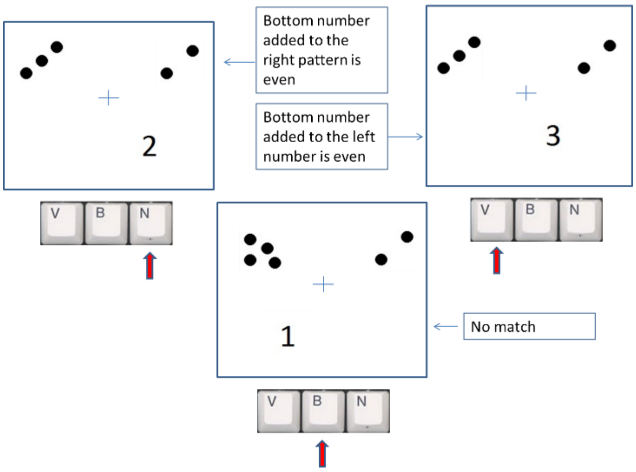

Figure 3.12: Visual instructions for participants present prior to completing fifth difficulty level.

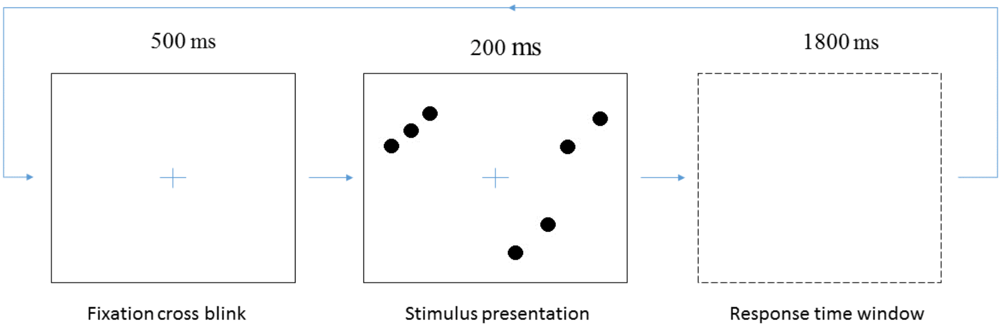

Figure 3.13: Timeline of events occurring in each trial.

After the experiment had finished, the participant was fully debriefed and thanked again for their time.

3.3 Results

Mean accuracy scores for each condition for each participant were exported from the experimental software. Mean reaction times were also exported. However, individual reaction times below 200ms were not included in this analysis since they were possibly the result of spurious processes (Whelan, 2007). Reaction times were taken from correct responses only. The data for two participants were removed from the analysis due to extremely low accuracy levels combined with extreme outlying RTs (above 2.5 SD). The main analysis represented the scores from both hemispheres within each of the levels of the match type independent variable. Therefore, scores from conditions relating to the location of the matching probe were collapsed (Table 3.1).

Table 3.1: Summary of data collected for matching probe locations corresponding to within and between hemisphere matches. Within hemisphere matches are displayed individually as well as collapsed over both hemispheres.

	Task Difficulty					
Match Location	**1 Mean (SD)**	**2 Mean (SD)**	**3 Mean (SD)**	**4 Mean (SD)**	**5 Mean (SD)**	**Measure**
Within Hemifield (L)	776(119)	931(163)	829(103)	972(157)	1061(209)	**Reaction Time (ms)**
Within Hemifield (R)	793(159)	947(155)	844(119)	928(185)	1055(236)	
Within Hemifield (Overall)	785 (134)	939(154)	836(108)	950(165)	1057(217)	
Between Hemifields	821(132)	939(151)	868(109)	967(164)	1092(207)	
Within Hemifield (L)	70(11)	67(16)	74(13)	55(10)	40(18)	**Accuracy (%)**
Within Hemifield (R)	72(16)	67(12)	74(10)	71(15)	44(19)	
Within Hemifield (Overall)	71(12)	67(12)	74(10)	63(11)	42(18)	
Between Hemifields	73(12)	58(9)	72(12)	63(11)	27(12)	
Within Hemifield (L)	1153(389)	1567(941)	1151(241)	1792(408)	3197(1579)	**Inverse Efficiency Scores**
Within Hemifield (R)	1286(910)	1466(404)	1163(258)	1383(456)	2696(886)	
Within Hemifield (Overall)	1172(476)	1442(354)	1146(199)	1545(384)	2847(957)	
Between Hemifields	1183(434)	1681(404)	1281(470)	1667(468)	3255(1686)	

A 2* 5 within participants ANOVA was carried out with probe position relative to the target, either within or between, as one factor and the level of difficulty as the other factor. The results of the ANOVA demonstrated a significant main effect for probe position (F (1,88) = 14.57, MSE = 2325.85, p<.01, η^2 = .40). Further, a significant main effect was found for task difficulty (F (4,88) = 18.61, MSE = 27155.33, p<.001, η^2 = .46) with a significant linear model (p<.001) demonstrating a clear increase over task difficulty in reaction times. However, no effect was found for an interaction between the two (F (4,88) = 1.52, MSE = 1752.91, p=.318, η^2 = .07).

A two-way ANOVA was also carried out on accuracy, represented by percentage correct. The results for the main effect of the location of the matching probe was significant (F (1,88) = 66.63, MSE = 22.41, p<.001, η^2 = .72). Furthermore, the main effect of difficulty was also significant (F (4,88) = 55.09, MSE = 201.77, p<.001, η^2 = .71). In the case of accuracy, a significant interaction was also found between level of difficulty and probe location (F (4,88) = 21.73, MSE = 26.77, p<.001, η^2 = .5). However, this appeared to be driven by similar scores over the first four levels of difficulty with a greater advantage for within hemisphere probe match location for the fifth level of difficulty.

Very little evidence of the speed accuracy trade-off was found with all but one condition showing no significant negative correlation between reaction time and accuracy (p>.05). Therefore, Inverse Efficiency Scores (IES) were calculated for each condition (Bruyer & Brysbaert, 2011). This took into account accuracy scores and was reported in ms with lower scores indicating more efficient performance. The IES was calculated by dividing the mean reaction time by the proportion of correct responses. A two by five ANOVA performed on the IES scores demonstrated very similar results to the initial ANOVA (Figure 3.14). A main effect for probe position (F (1,88) = 11.92, MSE = 161620.98, p<.01, η^2 = .35) and task difficulty reflected the original ANOVA (F (4,88) = 37.56, MSE = 723529.14, p<.001, η^2 = .63). Furthermore, no significant effect for the interaction between probe location and task difficulty was found (F (4,88) = 1.43, MSE = 179038.98, .p=.23, η^2 = .06)[2].

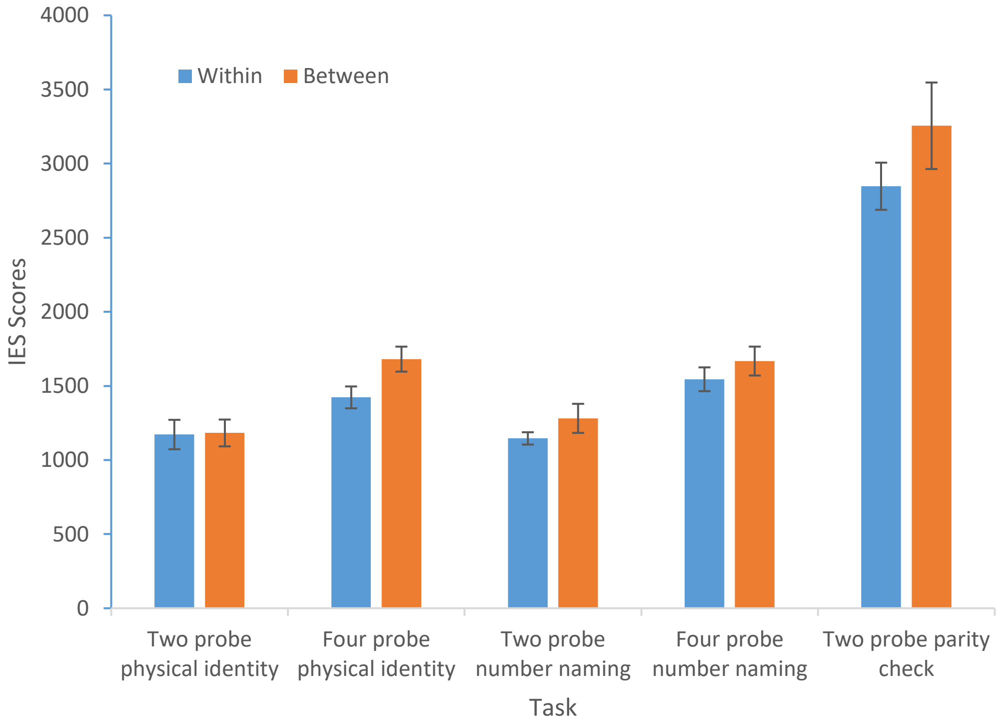

Figure 3.14: Mean Inverse efficiency scores (IES) for each condition over the levels of task demand. Error bars represent one standard error.

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[2] This analysis was also carried out with calculated medians. The results demonstrated the same main effects and no interaction. Probe location (F (1,88) = 6.144, p<.05), Difficulty (F (4,88) = 16.668, p <.001), Interaction (F (4,88) = 1.423, p = .233).

3.3.1 Differences in hemifield performances.

Comparison of IES scores for within hemifield matches between left and right probe locations demonstrated a main effect for task demand as expected (F (4,88) = 35.04, MSE = 697443.39, p<.001, η^2 = .61; Figure 3.14). Very little difference between reaction times between hemifields was observed with no main effect for probe location in reference to target, within or between hemispheres, (F (1,88) = 2.87, MSE = 601478.61, p=.105, η^2 = .12). However, an interaction between probe location and task demand was found with a left hemifield advantage for lower levels of difficulty and a right hemisphere advantage for the two highest levels of difficulty (F (4,88) = 2.75, MSE = 310773.24, p<.05, η^2 = .11). When the same analysis was carried out with the last three levels of task difficulty only, the main effect for task difficulty remained significant (F (4,44) = 52.98, MSE = 757363.95, p<.001. η^2 = .71). Further, a marginal interaction between task difficulty and location within hemisphere match was found (F (2,44) = 2.78, MSE = 310570.08, p=.073, η^2 = .11).

3.4 Discussion

The study in this chapter investigated the claim that the neural compensation associated with the reduction in hemispheric asymmetry observed in older adults is unrelated to age but rather due to task demand. From a behavioural perspective, the visual field paradigm, as utilised by Reuter-Lorenz et al., (1999), provided behavioural evidence for an across hemisphere advantage with greater task demand. The current study uses the same visual field paradigm to provide behavioural evidence in support of an age invariant compensatory mechanism which can be applied to any challenge, including task demand and age. Younger adult participants were presented with within and between hemifield matches represented by dot and Arabic representations with an increase in computational steps representing five levels of difficulty.

The results from the initial analysis in which reaction times and IES were collapsed across both hemispheres for within and between matches demonstrated that there was no interaction between task demand and probe position relative to the target, either within or between hemispheres. This finding suggests that younger adults do not gain increased benefit from across hemisphere matches at high difficulty levels compared to within hemisphere matches. Therefore, the between-hemisphere advantage observed in older adults is unlikely the result of an age-specific response to increased task demand.

3.4.1 Hemispheric differences

Investigation of the way in which the two hemispheres act independently of each other in response to within hemisphere matches revealed a difference between the two in response to increasing task demand. The results from comparison of left and right hemispheres for the within hemifield matches demonstrated an interaction between task demand and the hemisphere carrying out the processing with a right hemifield/left hemisphere processing advantage for lower levels of task demand which changed to a left hemifield/right hemisphere advantage as demand increased. This interaction approached significance when only those last three levels of task demand were included in the analysis. This trend might be indicative of a hemispheric preference related to task demand with the right hemisphere processes reserved for harder tasks. A left hemifield advantage was also observed by Guzzetti and Daini (2014) for younger adults in a name identity task but not for a less complex physical identity task. The current study reverses this pattern with faster responses demonstrated in response to left hemifield presentation of within hemifield matches at the lowest level of difficulty. Furthermore, at high levels of difficulty trends towards faster right hemifield presentations can be observed. Taken in isolation, these results may suggest some confounding effects of task type. That is, advantage for one hemisphere over another is the result in differing processing demands rather than increasing demands. However, only the last three levels of task demand were included in an analysis which included name identity task in relation to dots and Arabic number matches in all included levels. The near interaction in this analysis in which a small advantage for the left hemifield was observed which continued to become an increasingly larger advantage for the right hemifield. This suggests that it is task demand and not task type that drives hemispheric advantage in this investigation.

The results from this study provide an interesting comparison to previous results from imaging studies that have demonstrated increased activation contralaterally in response to higher task demands in younger adults (Cappell et al., 2010; V. S. Mattay et al., 2006). One of the points of comparison may be the difference in tasks used and their ability to facilitate neural compensation. This is discussed in the next section.

3.4.2 Task difficulty

This is the first time in which task demand has been increased to a level in which two computational steps are required to establish a match between items in a visual field paradigm. Therefore a number of methodological considerations need to be taken into account before a conclusion can be made as to how these results fit in with the current literature which suggests that neural compensation is age invariant.

Given that activation has been demonstrated in younger adults in response to increased task demand (Cappell et al., 2010; V. S. Mattay et al., 2006), one consideration may be that the level of task demand in the current study is not sufficient to elicit a compensatory response with those imaging studies which have demonstrated increased contralateral activation have used a working memory task to demonstrate this.

It is clear from previous studies that the amount of computational steps required to make a match represent an increase in task difficulty from increasing the amount of items on-screen. This has been demonstrated both in this study and previous incarnations of the visual field paradigm (Guzzetti & Daini, 2014; Reuter-Lorenz et al., 1999). However, what has not been compared is working memory load and computational steps in terms of task difficulty. Further, it is increases in working memory which have provided the challenge in which younger participants elicit contralateral activation. Since the nature of the visual field paradigm means that working memory plays very little part in successful task completion, integrating working memory to such a task would provide certain challenges. However, it may be that working memory and computational steps are simply not comparable in terms of load with increases in the need to keep information in memory overriding all of the processes in terms of task demand.

One of the suggestions for the difference in results between working memory tasks in previous demonstrations of contralateral advantage in younger adults and the matching tasks in this study is the ability of the participants to use strategies in the former and not the latter. Contralateral hemisphere activation has shown to be responsible for visuospatial strategy used to maintain information in short-term memory (Salmon et al., 1996). Therefore, younger adults may be using this additional strategy in the face of increased challenge. However, when it comes to the matching task used in the current study, the only available strategy is the speed accuracy trade-off which was known to be not applied to the current study due to the lack of negative correlations between reaction times and accuracy scores. Controlling for strategy change would be challenging so an imaging study with a matching task rather than a working memory task may be preferable for a direct comparison to be made.

The results of this study give further validation to the notion that computational steps can represent task demand. The current study provided a series of five levels of task demand which were represented by an incremental mix of perceptual load, numeric representation naming, and numeric representation naming with a parity judgement. Analysis of the IES demonstrates a clear linear relationship over the last three levels of difficulty. What was unexpected was the drop in efficiency given the introduction of trials which required the participant to match two different numeric representations of the same number. Unlike previous studies which have used physical identity matching and name identity matching (Guzzetti & Daini, 2014; Reuter-Lorenz et al., 1999), the current study included a task with name matching in combination with a lower level of perceptual load. Guzzetti and Daini (2014) kept the amount of probes constant and only manipulated whether or not the participants were required to match by physical identity or name identity. Reuter-Lorenz et al., (1999) used different levels of perceptual load but name identity trials were only used in combination with a high level of perceptual load. The finding that low perceptual load in combination with a name identity task elicits lower performance than just a higher perceptual load indicates the subtlety of change that inclusion of a single additional computational step makes. However, the increase in reaction time and variability of scores gained from the inclusion of two computational steps in the final level of difficulty suggests that this may be close to the maximum amount of difficulty that can be derived using this method.

On the final three conditions difficulty was dictated by the inclusion of additional computational steps combined with perceptual load. The final level of difficulty included two computational steps. In order to design a higher level of task demand than had been used previously, a decision had to be made with regards to whether or not the final level of difficulty should have included a high perceptual load as well as the two computational steps. The results appear to vindicate the decision to use only two probes in the stimulus set with a clear linear trend demonstrated over the last three levels of difficulty. The results gained from using a mix of perceptual load and computational steps also alludes to some independence of these processes.

This study has demonstrated that the difficulty of the task can be pushed beyond current boundaries with regards to matching tasks in a visual field paradigms. What the results have also uncovered is a potential difference in what it means for a task to be difficult. This has been manifest by the age invariance of the recruitment process related to working memory tasks in comparison to the lack of an advantage for across hemisphere presentation of perceptual matching tasks with additional computational steps used in the current study. Furthermore, latency scores over the five levels of tasks suggests two different projections relating to the two types of task presented to participant.

The difference in modalities of difficulty in this study suggest that there may be further ways in which task demand can be measured one of the questions that might be asked in future study is that how other types of task demand may be processed bilaterally. Conversely, confirmation may be gained as to task differences in neural compensation by implementing matching tasks in an imaging study. If contralateral activation in younger adults remains is not related to any benefits of performance then additional validation can be gained.

3.4.3 The split visual field paradigm

One of the main limitations of this study is the paradigm itself. Almost by definition the correct matches made, either between or within hemispheres, are forced due to the visual arrangement of the target and probe. Therefore, this approach lacks ecological validity as real-world processing would normally be the result of presentation somewhere in the intersection of the two hemifields. What this study cannot explain is the mechanism by which increased hemispheric communication would be driven. It is at this point one might look to the model in Chapter two for an explanation as to how between hemisphere, neural compensation might occur in the real world.

In continuing the comparison to the model in Chapter two, the model suggested age invariance due to the invariance of functionality of the biological components of the model over age. However, the current study suggests that increasing the demand per se is not sufficient to trigger interhemispheric communication in younger adults. This therefore suggests an additional trigger which occurs in late adulthood suggesting an interaction between the mechanism suggested in Chapter two and the age related decline of a potential barrier to this mechanism. One suggestion comes from the described functionality of the corpus callosum declining with age which in itself may not facilitate increased interhemispheric communication but might allow the mechanism described in Chapter two to function more effectively (Bastin et al., 2008; Schutter & Harmon-Jones, 2013). The interaction between an age invariant mechanism and a barrier to its facilitation may also support the idea that increased bilateral activation can be observed in younger adults but this is a sign of premature ageing, as suggested by the STAC theory (Park & Reuter-Lorenz, 2009).

Another possible limitation lies with the stimulus used in this study. As mentioned previously, additional computational steps appear to provide the right sort of load to represent task difficulty. However, what cannot be known, in relation to the visual field paradigm, is how difficult it needs to be. Theoretically, there may be a point at which younger adults demonstrate an across hemisphere advantage and that this occurs at an even higher level of task.

Future study might include integrating working memory into a visual field task in order to make direct comparisons with imaging tasks that have demonstrated contralateral activation in younger adults. In order to fully investigate the independence of perceptual load and computational steps in task matching, it is suggested that future research may include a reaction time analysis of these factors.

3.5 Summary

In summary, a visual field paradigm was used with a novel extension of task demand in order to investigate the age invariance of neural compensation. The results demonstrated a lack of a between hemifield advantage for younger adults at high task demand. This may be due to the difference in tasks used between imaging studies which have demonstrated age invariance and the current study. Contralateral activity in imaging studies may be due to strategy change, something which cannot be utilised in the current paradigm. Comparisons of within hemisphere matches revealed a difference over different levels of task demand. The successful use of a higher level of difficulty than has been previously used in a visual field experiment pushes the boundaries of this paradigm. This may provide a useful tool for future studies.

Chapter Four: Neural network models of Bilingualism and Cognitive Reserve[3]

"The limits of my language mean the limits of my world."

Wittgenstein

4.1 Introduction

The ability to speak more than one language has been hailed as one of the more recent test additions to the list of proxies of cognitive reserve (Bialystok et al., 2007). Whereas previous chapters have been concerned with investigating a compensatory branch of cognitive reserve referred to as neural compensation, the next two chapters represent neural reserve (Stern, 2009). That is, repeated use of neural pathways associated with a particular task results in a strengthening and consequential resilience of these pathways that may endure in older age. Multilingualism and bilingualism present an opportunity for the repeated practice of executive processes (Bialystok, Majumder, & Martin, 2002). This particular chapter presents a neural network model of bilingualism, within which it investigates what happens at the representational level as a result of encoding two separate languages over a period of time during which gradual age-related decline is implemented.

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[3] Aspects of this Chapter were published in: Rendell, N., & Davelaar, E. J. (2015). Semantic representations in monolingual and bilingual connectionist networks. *Journal of Cognitive Science*, *16*(3), 321-336.

The threshold model (Figure 4.1) suggests that whilst diagnosis of Alzheimer's may be offset in the bilingual group, the rate of decline may be greater since the model indicates that the actual neurobiological timescale for Alzheimer's disease is the same for those of both high and low cognitive reserve. However, in this study, no interaction was found between language groups and decline, measured using the MMSE across four years, of subsequent follow-up. Such a finding suggests that individuals with more than one language demonstrate the behavioural symptoms of Alzheimer's disease at a later age than monolinguals. What this study does not show is the biological passage of dementia prior to the individual experiencing the cognitive impairments associated with Alzheimer's disease. However, Bialystok et al. (2007) suggest that the similarity in the pattern of decline post diagnosis suggests that it is the biological onset of the disease which has been shifted by more than four years.

The study by Bialystok et al. (2007) also had a number of methodological issues including an imbalance between immigrant and non-immigrant participants. Control of immigration status is deemed important given that that many of the participants in the study were likely to be children and teenagers in Europe during World War II prior to migrating to Canada, where the original study took place. Given this background, a number of additional stressors may have existed that could have potentially confounded the study. This is also compounded by the further methodological limitation of a mixed diagnosis within the participants of both possible and probable AD. Whilst cognitive reserve has been known to apply to other conditions such as such as vascular dementia or frontotemporal dementia (Barulli & Stern, 2013) its contribution may be different to those alternatives, and therefore skew the findings.

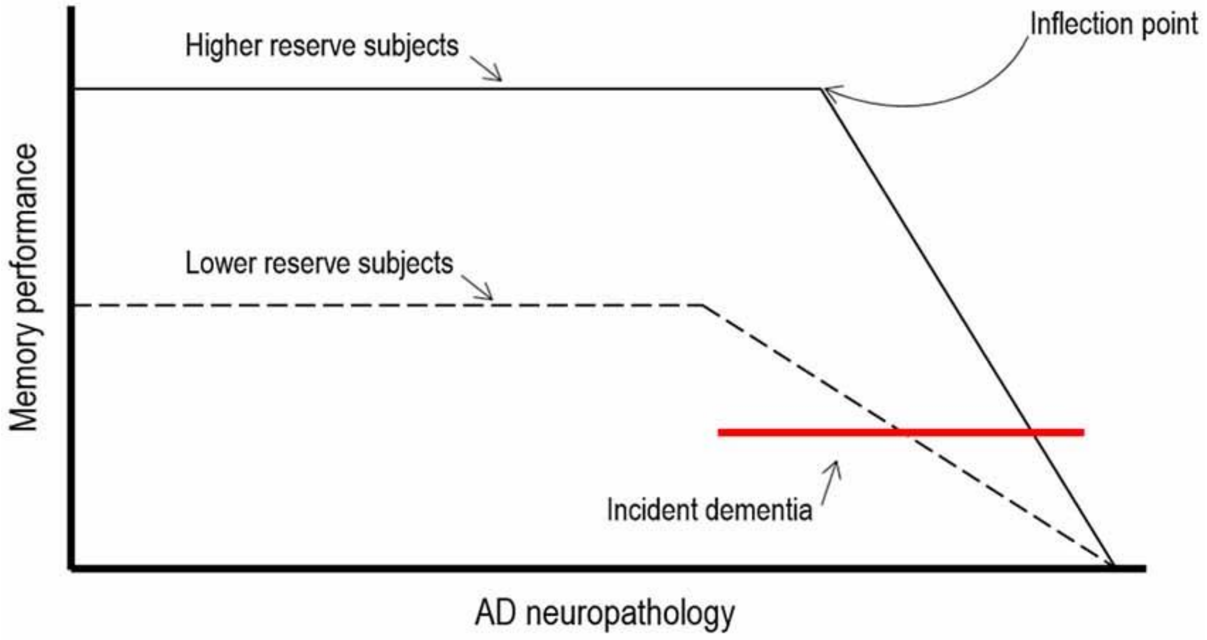


Figure 4.1: The threshold model (Satz, 1993), reproduced from Chapter one. Larger amounts of brain reserve mean a longer time period with dementia pathology prior to its manifestation at the behavioural level.

By virtue of location, a follow up study by Chertkow et al., (2010) provided a much greater mix of immigrants and non-immigrants. Multilingual immigrants and non-immigrant French/English speaking bilinguals were recruited from the Montréal area. Interviews were used to categorise 632 patients into three levels of language ability: monolingual (n=379) and multilingual (n=253), of whom 168 of the latter were exclusively bilingual. Importantly, initial age of symptom onset was gathered via family interviews rather than relying on the patient alone as in the previous study. Regular use of both languages was a specification for bilingualism. Furthermore, all patients involved in the study were given a diagnosis of probable AD alone. Results gained through multiple regression analysis controlling for the usual factors which may co-vary in a study regarding cognitive reserve did not fully replicate the previous study by Bialystok, Craik, and Freedman (2007). Whilst a protective effect was found for multilinguals, that is individuals with more than two languages, only a non-significant one-year offset of dementia diagnosis was found for multilinguals which included bilinguals. When the sample was restricted to individuals whom were considered non-immigrants, a factor lacking in the previous study, there was a significant difference but in the other direction, with monolinguals demonstrating a significantly higher age of presentation of symptoms than bilinguals. This last finding suggesting a confounding effect of migrant status.

In response to the findings of Chertkow et al. (2010), Craik, Bialystok, and Freedman (2010) carried out a further study in which more specific information regarding the multilingualism of the participants was gathered. Furthermore, the study also used those patients for whom a diagnosis of probable AD was provided rather than a mixture of possible and probable AD. The authors found that the original effect of bilingualism on both age of onset and age of presentation to the clinic endured with an offset of between four and five years of symptoms of AD with bilingual compared to monolingual patients. However, there was still an imbalance in the number of migrants and non-migrants which precludes interpretation of the absence of the effect of migration status. An imbalance in the numbers in each of the cells for the analysis in which no significant main effect was found for immigration status on onset age or age at which the patient approach might lead to the conclusion that immigration status may still provide a confound in the study. In a large-scale study, set in India, further attempts were made at controlling for immigration status. The study, in which 648 native individuals from India for whom bilingualism is born not from schooling (many of the participants were illiterate) or immigration but from necessity, found that bilingualism conferred a diagnosis of Alzheimer's disease or other dementia on average 4.5 years later than their monolingual counterparts (Alladi et al., 2013), a finding directly in opposition to the findings of Chertkow et al. (2010) in their sub-analysis of non-immigrants. Further, analysis of the illiterate participants revealed a delay of six years in bilinguals compared to monolinguals. This last finding provides evidence of the iaimsndividual contribution that language provides to cognitive reserve by controlling for the proxy of years of education.

Bak, Nissan, Allerhand, and Deary (2014) utilised the Lothian Birth Cohort to investigate the idea that being bilingual provides a cognitive advantage whilst controlling for education through the availability of baseline cognitive scores. The Lothian Birth Cohort is a group of English native speakers of European origin who were initially tested for a level of intelligence at age 11 in 1947. This allowed controlling for childhood intelligence, gender and socioeconomic status throughout the life span. The participants, then 73 years old, were further tested on fluid intelligence, memory, speed of information processing, reading and verbal fluency. The results demonstrated a protective effect for bilingualism with no negative effects of having more than one language. Reading verbal fluency and general intelligence were the most affected and general intelligence in particular was related to improvement in executive processes. This latter finding being of particular relevance to the current study since the model was based on the assertion that continuous use of specific executive processes such as inhibition and task switching may be at the seat of cognitive reserve at the cognitive level. Of further note was the similarity in performance between active (using second language) and passive (not required to use second language) bilinguals. Such a result may demonstrate that second language use at a developmental stage has greater long-term repercussions for cognitive reserve, even if not practised.

Craik et al. (2010) state that bilingualism and multilingualism contribute to cognitive reserve in much the same way as other demanding social activities do. Given that the mechanisms underlying any of the proxies of cognitive reserve are as yet unknown, it is not possible to state that any of them are similar to any of the others in terms of their contribution to offsetting cognitive decline. This is true both for the strength of their contribution and for the underlying mechanisms. What might provide a clue as to the way in which multiple language use contributes to cognitive reserve from a cognitive perspective is to understand the way in which practising multiple languages affects the central executive system. This perspective also provided the basis for the hypothesised contribution of multilingualism to cognitive reserve.

4.1.1 Bilingualism at the biological level

A biological description of higher cognitive reserve relates to the ability to sustain a comparable level of cognitive function but with fewer biological resources (Stern, 2009). For multilingualism to contribute to cognitive reserve, it should follow that those individuals who are able to speak more than one language should be able to sustain greater amounts of biological damage before manifesting symptoms at the behavioural level. Conversely, individuals with matched levels of cognitive performance should demonstrate different levels of biological decline with monolinguals demonstrating less damage than bilinguals since equal cognitive performance should be observed with access to less resources. For example, in individuals with Alzheimer’s disease, greater atrophy demonstrated by ventricular enlargements in the parietal region were found in individuals with a greater level of education (Kidron et al., 1997). Similarly, Stern (2009) reviewed a series of experiments carried out in the 90s in which proxies of AD pathology, namely rCBF were related to measures of cognitive reserve for AD patients matched on cognitive performance. The first study found a negative relationship between years of education as a proxy for cognitive reserve and lower levels of AD pathology (Stern, Alexander, Prohovnik, & Mayeux, 1992). Consequent studies found a similar relationship but with the addition of occupation and engagement with leisure activities as proxies for cognitive reserve (Stern, Alexander, et al., 1995; Stern, Tang, Denaro, & Mayeux, 1995). More recently, monolingual and bilingual AD patients who had been matched in terms of cognitive level and the clinical severity received Computerised Tomography (CT) to measure the level of medial temporal lobe atrophy sustained (Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). Forty patients with a diagnosis of probable AD were scanned. The scans were carried out as part of the diagnostic process and the researchers used digital callipers to take a number of measurements relating to ventricle size, a marker of AD progression with good inter and intra-rater reliability (R. Rossi, Joachim, Smith, & Frisoni, 2004). Results demonstrated significant differences in five of the nine measures taken with monolinguals demonstrating smaller volumetric shrinkage of the ventricles. Therefore, equivalence in cognitive function resulted in a higher level of cognitive reserve via bilingualism which meant that an individual could sustain cognitive functioning given a lower level of resources.

The reduction in biological substrate in bilinguals compared to monolinguals matched on cognitive performance provides evidence for the existence of cognitive reserve (Schweizer et al., 2012). However, to follow the monoist tradition in neuroscience would be to understand that what happens at the cognitive or algorithmic level must in some way be represented at the implementational or biological level. Therefore, it stands that the atrophy observed in individuals with a higher level of cognitive reserve as indicated by bilingualism must be getting their additional cognitive resources from somewhere at the biological level in order to underpin functionality of those regions subject to atrophy. One indication that this is the case for bilinguals is the evidence that points to a number of structural changes. For example, increases in grey matter density in bilinguals compared to monolinguals has been observed in the left inferior parietal cortex. This change decreases in size as the age of second language acquisition increases (Mechelli et al., 2004). Further, Della Rosa et al. (2013) found increases in grey matter volume in the inferior left parietal region which correlated with bilingual competence. In younger bilinguals (mean age 23.35 years), increases in grey matter volume in the Anterior Cingulate Cortex (ACC) also correlate with brain activity in the region as well as correlating with behavioural measures (Abutalebi et al., 2012). Further, in the flanker task, bilinguals showed lower levels of activation and increased cognitive performance than monolinguals indicating that ACC function was improved by bilingualism. The flanker task provides a measure of the ability to inhibit inappropriate responses given a particular context. Therefore, the flanker task measures executive processes associated with ACC function in terms of registering the conflict associated with incongruent stimuli (Kerns et al., 2004). Similar results with a different task have been found in a study by Gold et al. (2014) who found that older monolingual adults were outperformed by their bilingual peers in a perceptual task switching experiment. Furthermore, the increased performance was associated with a decrease in activation in the cingulate cortex as well as the left lateral frontal cortex. It is also reported that subcortical regions have also been augmented as a result of bilingualism. For example, greater grey matter volume was reported in the head of the left caudate nucleus in bilinguals as compared to monolinguals (Zou, Ding, Abutalebi, Shu, & Peng, 2012). Increased and grey matter volume has also been found in the left anterior temporal pole, targeted due to its speculated involvement in storage and differentiation between two languages(Abutalebi et al., 2014). Furthermore, increased grey matter volume in bilingual speakers positively correlated with word naming performance in the bilingual samples second language. From a global perspective, fractional anisotropy has uncovered higher white matter integrity in older bilinguals with the additional finding of a greater distribution of resting state functional activity in the areas where structural differences were observed (Luk, Bialystok, Craik, & Grady, 2011). Such a finding provides a functional correlate for the biological changes observed and may relate to the increased practice effect of bilingualism in some executive processes. These studies demonstrate that volumetric and functional increase in some areas may provide the cognitive offset to the biological decline observed in other regions when compared to matched monolinguals.

The relationship between such observed increases in grey matter volume in the regions relating to bilingualism and performance in the flanker task was further explored using older bilingual and monolingual adults (Abutalebi, Guidi, et al., 2015). The purpose of this investigation was to see if the increases in grey matter volume correlated with performance in the task. Initially, findings demonstrated a performance increase in the flanker task for bilinguals. Further differences between monolinguals and bilinguals were uncovered by the fitting of an ex-Gaussian distribution to the reaction times. This distribution comprises of a normal distribution with the addition of an exponential element, tau (τ), and is a better fit of the reaction time distribution which is usually positively skewed. This approach was also successfully applied in a previous comparison between monolingual and bilingual younger adults in which differences between both elements of ex-Gaussian distribution were uncovered(Calabria, Hernández, Martin, & Costa, 2011). Using fMRI analysis, Abutalebi et al., (2015) demonstrated age related decreases in grey matter volumes in the dorso-lateral prefrontal cortex (DLPFC) for both monolinguals and bilinguals. However, performance in the flanker task, measured by components of the Gaussian distribution of reaction times, correlated with grey matter reduction in monolinguals only. The lack of correlation between Flanker performance and DLPFC volume in bilinguals may be due to the more automatic nature of conflict resolution. This is because of the continual practice of executive control processes required in bilingual practice and the hypothesised source of the bilingual advantage (Bialystok et al., 2002). Further, the increase in biological substrate related to bilingualism might provide a buffer against observed in other areas. Therefore, this type of cognitive reserve defines itself as the neural compensation if it reinforces cognitively unrelated areas (Stern, 2003). However, if it is the strengthened existing pathways which are involved with language that directly contribute to offsetting age-related decline then the term neural reserve, rather than neural compensation, might be applied (Stern, 2003). Given this, investigation is required at the biological level to uncover the mechanisms and pathways by which the additional substrate or higher functionality provides a compensatory action. One could speculate that as well as providing a conflict-monitoring role for the executive processes exclusively related to language production in bilinguals, the ACC may also be complicit in triggering compensatory processes by monitoring task demand. This application of ACC function was demonstrated in Chapter two.

4.1.2 Bilingualism and cognition

To understand what it is about bilingualism that confers an advantage to cognitive ageing from a cognitive perspective, one can first observe the effects of bilingualism on cognition in a more general population. In terms of nonverbal effects, these are wholly positive. Initial findings in a study comparing English only speaking Canadian children with their French- English speaking counterparts on verbal and nonverbal tests found that the bilingual children outperformed the monolinguals in almost all aspects, especially the nonverbal intelligence tests (Peal & Lambert, 1962). Equivalence was found in visual perception but advantages were found in symbol manipulation. The difference in the increased ability in symbol manipulation but not visual perception highlight the difference between representational knowledge and executive control processes and the contribution that being bilingual makes to increasing proficiency in each. Representational knowledge is related to the ability to encode problems in enough detail, make the appropriate logical inferences, and access the relevant knowledge (Bialystok, Craik, Klein, & Viswanathan, 2004). There may be some use of these abilities in the production of language for bilingual individuals. However, the majority of bilingual language production relies on executive control mechanisms. To be able to speak the correct language under the appropriate circumstances takes repeated use of executive functions to select the appropriate language, activate whichever representations are appropriate and then finally inhibit the language that is not being used (Paap & Greenberg, 2013).

It should follow therefore, assuming any transfer out of the language domain, that the majority of advantages found between monolinguals and bilinguals would reside in the domain of cognitive control. Evidence has already been discussed in relation to the Flanker task and a bilingual advantage is also found in the Simon task (C.-H. Lu & Proctor, 1995). However, the development of cognitive control processes appears to diverging from monolinguals to bilinguals at a young age. Bialystok (1992) provided monolingual and bilingual children with an embedded figures test. The purpose of the test was for the children to find a simple pattern concealed within a larger more complex figure. For example, a house shaped configuration and the child was required to identify a simple triangle shape. Bilingual children performed better in this task than their monolingual counterparts. These findings were interpreted as showing that bilingualism conferred an advantage for the children due to increased ability to inhibit irrelevant or unwanted information.

An advantage for bilingualism has also been found in more complex tasks requiring multiple aspects of cognitive control. For example, in a task known as the dimensional change card sorting task, bilingual and monolingual children between the ages of four and five years were asked to sort images that varied on the dimensions of shape and colour (Bialystok, 1999; Bialystok & Martin, 2004). Specifically, they were required to put the cards into boxes according to a rule based on one dimension (e.g. colour). However, later in the task the participant would be required to switch and sort the cards according to another dimension. For example, this might mean putting circles in one box and squares in another whereas later on the participant might be required to sort the same stimuli into different boxes by virtue of their colour. The results of the study demonstrated a significant difference between monolinguals and bilinguals in the ability to perform this task. Both sets of children performed equally in the initial trials prior to the change in rules being initiated. The subsequent divergence in performance between the two groups was postulated to be the result of the difference in abilities to switch between the rules as well as in inhibiting the rule that was not relevant at the time. All of the above studies demonstrate an increased capacity for the inhibition of information. It is this continuously practised inhibition that may lead to the generation of cognitive reserve through the strengthening of the networks underlying this particular function. What remains to be seen, however, is the nature of the mechanism itself which is being practised.

The advantages found for bilinguals and cognitive control have also been demonstrated to relate to the some aspects of syntactic ambiguity resolution using garden path sentences (Teubner-Rhodes et al., 2016). A garden path sentence is grammatically correct but starts in a way that the initial interpretation is most likely incorrect. Fifty nine Spanish – Catalan bilinguals and 51 Spanish monolingual participants were given an N-back task which included both conflict and non-conflict trials. The ability to correctly parse garden path sentences in real time as well as through post-test comprehension probes was tested both before and after practice of either the no conflict or high conflict N-back task. The authors found a bilingual advantage for the high conflict N-back trials as well as sentence comprehension, measured by off-line comprehension probes. However, no bilingual but advantages found for the ability to parse a sentence in real-time. The authors speculate that any advantage in this aspect may be offset by observed latencies in lexical access, described below.

In addition to the advantages, the linguistic deficits associated with having more than one language are equally well researched. For example, it is generally accepted that one of the predominant negative effects of bilingualism is the vocabulary size. This is generally smaller compared to monolinguals for both languages spoken (Mahon & Crutchley, 2006; Portocarrero, Burright, & Donovick, 2007). However, equivalence in vocabulary size for L1 between monolinguals and bilinguals has been found in very young children (age 24 months; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

Bilinguals also appear to have more trouble accessing particular words. Picture naming tasks have shown that bilinguals are slower than their monolingual counterparts (Gollan, Montoya, Fennema-Notestine, & Morris, 2005; Roberts, Garcia, Desrochers, & Hernandez, 2002). Further, verbal fluency tasks in which participants are asked to name as many words as possible for a given category or categories, have demonstrated a disadvantage for bilinguals (Gollan, Montoya, & Werner, 2002; Rosselli et al., 2000). What is of note, however, is that when vocabulary size is taken into account, deficits in lexical access are diminished or disappear completely (Bialystok, Craik, & Luk, 2008a). This suggests that these effects are due to a smaller vocabulary rather than processing differences. Further effects of bilingualism on cognition include tip of the tongue errors which are more frequent in bilingual speakers (Gollan & Acenas, 2004) and it is also reported that bilinguals have trouble identifying specific words through noise (Rogers, Lister, Febo, Besing, & Abrams, 2006).

4.1.3 Retrieval induced inhibition

The studies in this chapter are based on the proposal that the advantage for bilinguals in inhibitory-based tasks and therefore cognitive reserve may arise from the application of greater inhibitory mechanisms when retrieving both lexical and conceptual representations. The motivation for such an idea comes from the theory of retrieval induced inhibition (Anderson, Bjork, & Bjork, 1994). This theory suggests that the observation that retrieval of one memory can inhibit the recollection of other, similar memories is due to the recruitment of inhibitory processes which serve to discriminate between the target representation and similar representations. The models in this chapter also represent inhibition at different levels of language processing, the conceptual and lexical. This is further to a theory and computational model of inhibitory control (IC), proposed by Green (1997) and described later in this chapter.

Retrieval induced inhibition is a robust effect has been observed in a number of circumstances (for a review, see: Storm et al., 2015). Studies which demonstrate this effect usually take on a similar three-part procedure, known as the retrieval practice paradigm. Firstly, the participant is required to remember a number of word pairs which are made up of one of several different types of category and then an item which belongs to a category, for example the word pairs or *fruit – banana* or *drink – whiskey*. Participants are then required to practice retrieval when given a category name plus cue letters. For example, *fruit –ba…* or *drink –wh…* The last part of the study requires the participants to attempt to recall all of the items given the category and sometimes additional cue letters. Retrieved items are therefore placed in three categories: where both the items and the categories have been practiced (Rp+), non-practised items from practice categories (Rp-), and items from non-practiced categories (Nrp). Performance is best on the Rp+ items, as would be expected. However, the decline in performance comes with Rp- relative to Nrp items. This difference occurs due to the recruitment of control mechanisms. As such, greater similarity of representations leads to greater recruitment of inhibitory processes.

Single recollections of semantically-related information have been demonstrated to be faster, a process known as priming. However, repeated recollection of semantically-related representations will increasingly inhibit the recollection of other, semantically-related information (Johnson & Anderson, 2004). Semantic retrieval forgetting had been demonstrated by the use of homographs in which a word such as *prune* will have a dominant noun meaning (“fruit”) and a subordinate verbal meaning (“to trim”). Asking participants to generate a recollection using letter cues for the subordinate verb meaning would mean that participants would have to inhibit other semantic meanings, in this case the meaning relating to fruit (Simpson & Kang, 1994). In a two-part study, the first using homographs and the second using non-homographs, Johnson & Anderson (2004) demonstrated that recollection of semantic information was impaired on a subsequent free-association test under both circumstances. Furthermore, impairment also occurred regardless of the semantic nature of the cue in the free-association stage of the experiment, meaning that inhibition occurred purely based on the semantic nature of the recalled representation. This study demonstrates that inhibition also occurs in the recollection of semantic memory. In the context of language, increased inhibition in bilinguals compared to monolinguals may involve similar inhibitory processes for bilinguals to deal with the bilingual-specific property of cross-language competition.

4.1.4 Modelling language

A biological perspective has been given above which discusses the advantage in terms of the increase of grey matter in specific brain regions related to bilingualism and in some cases cognitive control. Furthermore, the potential cognitive mechanisms which have been exercised as a result of using more than one language has been explored. Models can provide information in three areas; understanding and characterising the problem, examining the availability of information and its representation and evaluating and understanding the solution (Dror & Gallogly, 1999). Furthermore, the data acquired from models allows for predictions to be made. This investigation will use connectionist models to characterise language learning in both monolinguals and bilinguals. The following section provides an overview of connectionist modelling and its application to bilingualism.

4.1.5 Connectionism

Along with a departure from strong symbolic representations, connectionist philosophy rejects the idea of the rules that manipulate them. This stance has been validated by Dror and Dascal (1997) who demonstrate that any number of rules can be applied to a specific outcome. They give the example of the sequence of numbers 2, 4 and ask by what rules can these numbers be both generated and continued. The answer is that any number of rules can be applied, for example, the addition of two each time or multiply the preceding number by two. These are two examples but there is an infinite number of ways in which the sequence can be generated and continued using increasingly complex rules, thus diluting their explanatory strength.

The question of levels of description in neural networks is also brought up in classic studies within the field. Rumelhart (1986) describes a neural network in terms of operating on a ‘micro level’ when related to a schema, the symbolic currency of cognition. A schema represents a concept; the individual units of a neural network represent smaller features of a schema or ‘microfeatures.’ Due to the lack of symbolic representation ascribed to each microfeature, Smolensky (1988) termed neural networks as ‘sub-symbolic’.

Describing the advantages of modelling cognition with connectionist networks encourages the reader to view classical and connectionist models in opposition. Broadbent (1985) situates classical models of cognition as providing explanation on an algorithmic level which means that connectionist networks reside ‘only’ on an implementation level. This view was refuted by McClelland and Rumelhart (1985) who stated that connectionist networks also reside on the algorithmic level and therefore are in direct competition with classical models. However, both approaches have also been viewed as complimentary. Estes (1988) examines the possibility of a learning connectionist network coupled with a symbolic memory array in order to provide judgement for categorisation.

The view carried forward in this thesis is that connectionism is biologically inspired. This does not necessarily mean that connectionist models only provide answers on an implementational level since the algorithm used is in some way dependant on the hardware that runs it (Marr, 1982). Therefore, connectionist models that provide similar output to the results of behavioural tests on humans provide both answers on an algorithmic level as well as attesting to the biological validity of connectionism. In bridging this gap, connectionist models provide a leash on cognitive theorising by providing evidence that restricts the choice of competing classical cognitive models as well as providing evidence for new theories through lesioning of the models themselves. This difference provides a bridge for the gap that exists between classical models of cognition and the functionality of the brain (Churchland & Sejnowski, 1988).

4.1.1.1 Biological plausibility of neural networks

The history of connectionism and the contributions made by Hebb (1949) demonstrate the connection between artificial connectionist networks and their biological counterparts. In this section that relationship is examined in more detail. Whilst backpropogation cannot be directly related to biological processes, there is more than a subtle comparison between the structure and implementation of connectionist networks and the human brain. On current estimates there are approximately 100 billion neurons in the human brain (Pinel, 2013). Neurons may be arranged in groups of hundreds of thousands to millions but they are largely interconnected in a natural neural network in which processing is parallel. Therefore, no one neuron has a greater capacity to process information, on a task basis, than any of the others.

Neurons communicate from one part of the neuron to the other electrically via *action potentials*. Between neurons, communication takes on a chemical form enabling chemical messages to be passed across the gap between them or *synapse*; these chemicals are known as neurotransmitters. When the amount of neurotransmitter in the synapses between one neuron and those adjacent to it exceeds its threshold that neuron will ‘depolarise’ at its point of connection to the other neurons. The depolarisation will continue along the neuron in the form of an action potential and pass the activation to adjacent neurons. Due to the threshold operation of the neuron the signal that travels onward has an 'all or nothing' effect. Some neurotransmitters are inhibitory; rather than depolarising they hyperpolarise the neuron, making neural transmission less possible. In sum, the activation of a neuron is dependent upon the incoming activation of the neurons connected to it.

The operation of a connectionist network is similar in some fundamental aspects to that of a real neural network. Firstly, computation is dependent on a number of individual units. These can be analogous to artificial neurons and, as with real neurons, their operation is also dependent on incoming activation. The all or nothing effect of the neuron is manifested in the binary input of the connectionist network. Input is represented in '1's and '0's and any number can make up an incoming stimulus. The modulatory effect of receptor numbers and neurotransmitter amounts is represented by each incoming connection having a variable weight. Depolarisation and hyperpolarisation are simulated by positive and negative weights. The afferent activation (**i**) is multiplied by the weight (**w**) on the afferent connection (Figure 4.2). The total afferent activation is then processed by a transfer function. Typically, this is of a sigmoidal nature, thus transforming the afferent activation to values within a range of -1 to +1 for a log sigmoidal transfer function or 0 to + 1 for a tan sigmoidal transfer function.

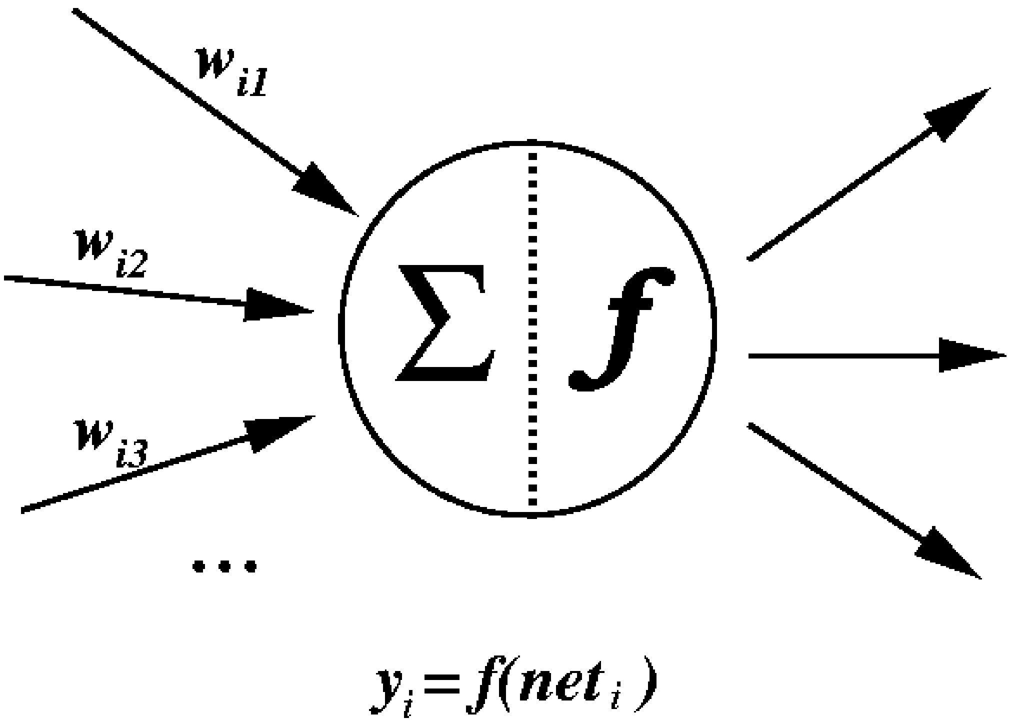


Figure 4.2: Artificial Neuron with three inputs. Activation from all three afferent connections (ix) is summated and efferent activation is determined by the transfer function (f).

There are some features of computational models do not appear to be implemented in biological neural networks. Biologically implausible features, such as the backpropogation algorithm, have been thought to invalidate computational models as implementational models (For example Grossberg, 1988) and are therefore of no use as tools of investigation. Dror and Gallogly (1999) argue that this may not necessarily need to be the case. One answer to the problem of backpropogation is that it is a means of training the network and once carried out, the fully trained connectionist network is biologically plausible. They also state that while biologically plausible models of cognitive processes are valuable to cognitive research, biologically implausible models of cognitive processes can provide a number of insights into this area (Dror & Gallogly, 1999). Furthermore, even if backpropagation were biologically implausible, it still has application in neurobiological studies, for example, the investigation of the functionality of interneurons (Müller, Reinhardt, & Strickland, 2012).

One of the most influential, biologically analogous methods employed when using connectionist networks is to damage or *lesion* them to produce behaviours similar to in vivo studies of brain-damaged patients. This can be carried out in a variety of ways, from removing nodes to removing connections between nodes. Connectionist networks can be built to carry out specific cognitive functions and damage can be carried out ‘to order’ of a type and level that replicates the behavioural patterns of deficit common to a disorder. The Hinton and Shallice (1991) model of deep dyslexia is one well-known example of damage to a connectionist network producing patterns of deficit observed *in vivo*. Traditional models of deep dyslexia interpret semantic similarity and phonological difference in word repetition tasks as a break down in a dual-route model that separates semantic and non-semantic processing (Morton & Patterson, 1980). However, other behavioural anomalies, for example, the visual error observed in deep dyslexics such as responding with SANDAL instead of SCANDAL (McLeod, Plunkett, & Rolls, 1998), cannot be explained by damage to either route. The Hinton and Shallace (1991) model reproduced these errors (their model produced COT instead of CAT) and demonstrated that damage to any part of a distributed network could reproduce these errors in the absence of specific processing routes. Furthermore, Rueckl and Dror (1994) provide a detailed account of the results in terms of the activity and functional properties of the connectionist network.

Much of classic cognitive science relies on the assumption that the brain is a symbolic computing machine. This is underpinned by the belief that the main structural requirement for intelligence is the storage and manipulation of symbols (Newell & Simon, 1976) . In practical terms this is a view of the brain as a computing machine. The brain is a ‘machine’ that uses representations that are analogous to data structures which are in turn manipulated by procedures (Fodor, 1975) . To model within this paradigm, a symbolic form of computational modelling is used. In these models, the level of representation of the model is a descriptive one and all of the processes contained within can be explained in terms of the functions that they execute. Symbolic approaches rely on a belief that all mental functions can be formalised into a framework that relies on a set of rules and procedures. Symbols take their place in the framework as the tokens from which the rules and procedures are built.

4.1.1.2 Parallel Processing

There are many different types of connectionist network but the basic concept is the same. The function they perform is distributed in parallel over a number of units or nodes (Figure 4.3). For clarity the processes described will be more specific to the type of neural network used in this investigation although there are commonalities within connectionist models as a whole.

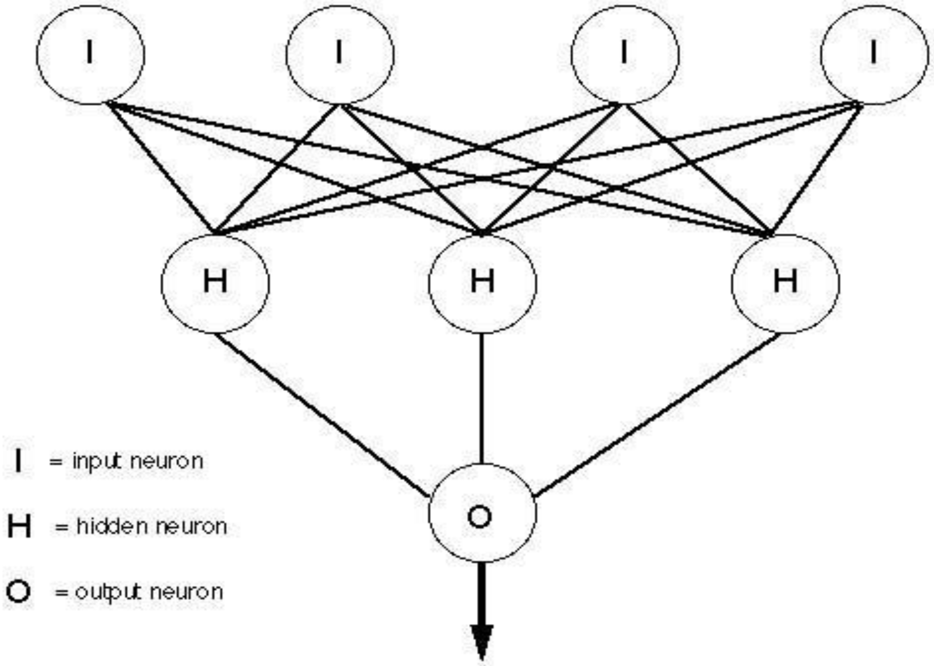


Figure 4.3: A simple, two layer (output not included in layer count) connectionist network. all neurons or nodes in the network have the same functionality and operate in parallel to one another.

The parallel architecture of the connectionist network lends itself to a number of features that demonstrate a similarity to the way in which the human brain functions. These are described by McLeod, Plunkett, and Rolls (1998) and the most pertinent will be described here. The key property of connectionist networks is that representation and function within the network is *distributed*. Storage of information is distributed over the weights of the network, contrasting the specific memory addresses of personal computers and the localist storage system of classical models of cognition.

The way in which information is stored in a neural network lends itself to a number of properties that would not be present in a symbolic system. One property that stands out is *damage resistance or fault tolerance*. Because each node of the network contributes equally to the processing, damage to the system will result only in partial loss, which is in relation to the severity of the damage. This, *graceful degradation* (Erman, Fennell, Lesser, & Reddy, 1976; Mcclelland, Rumelhart, & Group, 1986) is in contrast to the result of damaging a localised, symbolic, system which would involve breakdown of one function whilst leaving others intact.

Another property of distributed neural networks is their *content addressability*. A direct, functional comparison can be made between human memory and information stored by connectionist networks. In contrast, conventional computers store information in addressed memory locations. The advantage of content addressability is that information can be accessed by the recollection of any feature of the memory rather than the address itself.

The ability of neural networks to *generalise* a function from a fairly limited learning set of inputs and outputs also sets connectionist networks apart from classical symbolic, cognitive architecture. The pervasiveness of this property has led to the term ‘universal function approximator’ (Hornik, Stinchcombe, & White, 1989), used as a descriptor of a multilayer connectionist network. The ability to generalise is one of the approximation of a function as represented by an initial subset of inputs taught to the network. When novel data is presented to the trained network, the model produces an output based on the function that it was trained to perform. Since classic cognitive models rely on a framework of rules and procedures built from semantic ‘tokens’ which rely on input defined within that framework, they cannot process input that is previously undefined.

Graceful degradation, content addressability and the ability to generalise are the basic properties and functioning of a generic neural network. These properties arise due to the distributed way in which representations and processes are stored within the network. There are many variations on this theme such as autoassociators and self-organising networks but the basic functions and properties remain the same.

4.1.1.3 Training a connectionist network

Connectionist networks and their biological counterparts are dissimilar in one major aspect. Connectionist networks cannot carry out any functions unless they are trained to do so. Even when learning is unsupervised, the network consists of a random set of unaltered weights that do not carry out any particular function. Although learning is also a large part of human and animal experience, certain behaviours, such as nipple seeking, are hardwired and the ‘weights’ of the connections between the neurons are predetermined (Schaal et al., 2003). In supervised learning with connectionist networks, such as that carried out in the experiments in the following chapters, learning is achieved by presenting the network with a series of inputs. The error between the networks actual outcome and the desired outcome is calculated and adjustments are made to the weights relative to this calculation. The adjustments are carried out in a series of trials or *epochs* in which a large amount of different examples of the same function are given as inputs and outputs to the network.

4.1.6 Localist models

Whilst localist models of language acquisition are not the methodological subject of this chapter, one or two models are worth noting. The Bilingual Interactive Activation (BIA) model (van Heuven, Dijkstra, & Grainger, 1998) used a connected localist network to model bilingual visual word recognition. Different linguistic representations are represented by four hierarchical levels. Upon presentation of a word to the model, the features of the constituent letters of the word are activated in the model. The activation of those features in turn activates the letters which are part of the word presented. The letters activate the words of the language and the word subsequently activates the language notes to which they are connected whilst simultaneously feeding back activation to the letter level. Inhibition is present in this model through the action of the language nodes in inhibiting candidate words from other languages as well as lateral inhibition between lexical candidates. The result of the presentation of initial word is that it becomes the most active word unit and can be considered identified. The BIA+ model, an extension of the original model (Dijkstra & van Heuven, 2002) includes additional levels of processing via phonological and semantic representations the latter meaning that determination of the actions to be executed for the task at hand is also based on relevant information. Further differences with the BIA model include a lack of interaction between the decision-making subsystem and the word identification subsystem. Further, the bottom up nature of BIA+ means that there is no inhibitory influence from language membership upon activation levels of the word identification system.

In placing the notion of inhibition in bilingualism in greater prominence, Green (1998) produced an inhibitory control (IC) model of bilingual language use. The model focuses on task demand and contains three separate aspects. The first involves competition between language tasks schemas, defined by the author as put in place to carry out a specific task, in order to control output. The second aspect relates to the lemma level (Levelt, 1989), a level of language production which relates to the locus of word selection. In this case, as with other models discussed in this chapter, the localist symbols within each of the languages were tagged accordingly. The way in which the correct language is produced in the IC model is via the inhibition of tags at the lemma level. This is carried out by the Supervisory Attentional System (SAS) upon language tasks schemas which compete to control output. The result of this inhibition leads to the exertion of control at the lemma level. A number of predictions were made with regards to the existence of costs incurred by switching languages due to inhibition being applied to the tag of a specific language. Further, interfering stimuli in the Stroop task was predicted to be ameliorated by increased control in the word reading schema of L1. This study paints a picture of inhibition applied on a language wide basis. The models in the current study aim to demonstrate that increased inhibition can also be applied when recalling individual items. Further, the current study also assumes that inhibition is also applied when making distinctions between categories.

4.1.7 Connectionist models and language

In general, connectionist models have contributed significantly to language as a whole. For example, speech recognition (McClelland & Elman, 1986), the processing of sentences (McClelland & Kawamoto, 1986) and acquisition of English past tense (Rumelhart & Mcclelland, 1986). Unfortunately, distributed models of bilingualism are in short supply. However, a few models exist and the first of these described in this section relates to the development of the organisation of language. Experiments in semantic priming have supported the view of a single conceptual store for bilingual semantic memories with dual stores for each lexicon in a bilingual due to the absence of cross-language priming (Fox, 1996). The bilingual simple recurrent network model (BSRN) of bilingual learning suggests how this organisation may come about (French, 1998). In this model, separation of words in sets of sentences in two micro languages was produced by a feedforward network with the addition of a set of context units connected to the units in the hidden layer. These maintain a copy of the previous values and the result is that the network maintains a type of state. The model produced an overlapping set of representations but clustering of each of the two languages was also present. However, the network was able to distinguish them by the differences in the activation patterns for each language. In the case of this model closeness of representations is demonstrated and may provide additional computational evidence for the need for inhibitory mechanisms to prevent the unwanted language from interfering.

Another way in which connectionist models have represented the development of language is through the use of self-organising networks. Such networks belong to a class of unsupervised neural networks, as the learning does not require any explicit teaching but achieves learning through organisation based on features of the input. During the learning process an internal representation is gained from the multi-dimensional input space and represents itself on a two-dimensional topological structure (Kohonen, 1982, 1998). The specific application of self-organising networks to bilingual language development comes in the form of a self-organising model of bilingual processing (SOMBIP; Ping Li, 2002). This model used two interconnecting self-organising networks for lexical phonology mapping, SOM 1 and

SOM 2. Each of the two networks self-organised on word forms and word meanings respectively. Furthermore, the networks were coupled with a recurrent neural network. Unlike the BSRN model, the SOMBIP model used realistic linguistic data as an input to the network but like the BSRN model, no language tags were used to differentiate words between one language and another. As with the BSRN model, the SOMBIP model was able to recognise individual patterns within each of the language lexicons in the absence of any layers dedicated to language or tags representing the language attached to each of the inputs. Differentiation of lexical semantic categories was achieved purely through the self-organisation process.

Both the SOMBIP and BSRN models demonstrate that separation of representations, either between languages or within them can be successful purely because of the features of each of the realistic language inputs. In the case of the SOMBIP model (Ping Li, 2002), simplistic representations of both the lexical form map and the semantic map produced by the network demonstrated distinct clusters of both English and Chinese languages. This was true of both form and meaning. However, in this case, no clear metric was applied to measure the level of separation between the two languages on both of the levels. A more advanced method of demonstrating separation within and between two languages was the cluster analysis employed by French (1998). This demonstrated that clustering could occur both on a level of language and also in terms of categories. The technique was also applied in the same study to investigate the stability of the languages in the face of lesioning. The results demonstrated that stability of the language frame work could be affected by removal of crucial nodes in the hidden layer. This demonstrated that whilst processing and memory is distributed over a network, some nodes are more important than others in their contribution.

The third connectionist model discussed in this section differs from the SOMBIP and BSRN models in that the input languages were tagged to differentiate them. The tag itself might represent phonological or contextual information which differentiates between the two languages in real life. The model used a single neural network to represent dual language storage language over a single resource with the notion that this is the basis of interference effects (Thomas, 1998). These are the result of studies which demonstrate that recognition of words which are similar in their form but not in meaning are slower than cognate homographs which are similar in both form and meaning (Klein & Doctor, 1992). As such, the purpose of the model was to replicate the interference effects as well as represent the separation of the two languages. One hundred words in each of two artificial languages was used. These were constructed of input patterns which represented the consonant-vowel relationship with orthographic representations that were either specific to a language or shared across both of them. Principle component analysis was applied to the 60 dimensions represented by the activity levels of the nodes in the hidden layer of the model to visualise the separation of representations in the two languages. The results showed that in this model the two languages were able to be separated within the same resource. In addition, the study demonstrated the usefulness of tagging as a way of differentiating between languages in representational space.

The SOMBIP and BSRN models have demonstrated that the use of language tags is not necessary to produce language separation. The simulations in part two of this chapter investigated the separation of representations due to differences in the number of languages in each network rather than categorisation due to input features. As such, the input vectors were randomised to control for differences that may confound this. However, in order to provide a controlled level of separation between both languages and categories within languages, tags were used at the end of each input factor to identify them as belonging to a specific category and language.

4.1.8 Simulating the ageing process in neural networks

One of the aims of the current study is to investigate the development of representations, either lexical or conceptual, over the entire lifespan. Whilst neural networks are almost defined by their ability to represent the development of memories or functionality (Hinton, 1989) the challenge is to represent neurobiological ageing in some way. One of the most common ways in which pathology in general is represented in neural networks by incrementally removing nodes of the network, commonly known as lesioning. This method has had some success through matching the performance of lesions to the patterns of behavioural deficits observed in brain damaged patients. For example, connectionist models of reading aloud have reproduced a number of factors that have been observed *in vivo*. One such model by Seidenberg and McClelland (1989) was taught to pronounce 3000 monosyllabic words. Using errors between actual and desired output as an indication of speed of response, the model demonstrated an accurate replication of the speed of recall for more common words. An interaction between frequency and regularly pronounced/exceptional words as well as an interaction between the number of words with similar spelling and frequency were also found, both of which occur with normal adult readers when reading aloud. Further models utilising lesioning in the have investigated acquired dyslexia (Hinton & Shallice, 1991) as well as category-specific semantic deficits (French & Mareschal, 1998).

Applications of lesioning to replicate both age and Alzheimer’s disease are limited. This is perhaps due to the diffuse neural damage observed in Alzheimer’s disease (French & Mareschal, 1998) and the diffuse but much more subtle decline observed in healthy older adults. Whilst the latter could be simulated through a network with many tens of thousands of nodes in its hidden layer, lesioning is best used as a proxy of neurological insult.

Another manipulation which has been brought to bear on a connectionist network to represent some biological change is the adjustment of the learning rate. Reggia, Goodall, and Shkuro (1998) represented differences in hemispheric plasticity in a recurrent connectionist model which was trained to generate phoneme sequences to simulate reading aloud. The aim of the study was to investigate the ability of two hemispheres to lateralise functions. Their study demonstrated that plasticity, as represented by a higher learning rate was one of the contributing factors towards lateralisation of an individual hemisphere.

Increased learning rate regulates a hemisphere model as a proxy of hemispheric plasticity. This has demonstrated a more favourable environment for localisation of function in a visual character recognition task (Shevtsova & Reggia, 1999). Simulating ageing through the adjustment of overall learning rate is favourable from a practical point of view. Evidence exists that region such as the medial temporal lobe and prefrontal cortex undergo some decline (Burke & Barnes, 2006). However, plasticity may be retained to a reasonably good level throughout the adult lifespan with factors such as physical activity and stimulating environments moderating its decline (Kramer, Bherer, Colcombe, Dong, & Greenough, 2004; Mahncke et al., 2006).

The way in which the current study represents the ageing process is through a more subtle manipulation which reflects dopaminergic decline during age. The motivation for adjusting dopamine occurrence within the brain comes from the dopamine hypothesis (Bäckman et al., 2010) which was explored in Chapter one. There is evidence linking the observed decline in dopamine from early to late adulthood (Glickstein, Desteno, Hof, & Schmauss, 2005; Luciana & Collins, 1997) to the cognitive deficits observed over age. The crux of the proposition by Bäckman et al. (2010) is that dopamine performs a modulatory function in some cognitive functions. For example, measures of striatal dopamine relates strongly with magnitude of the BOLD response in reward-related learning (Schott et al., 2008). Further, a working memory related delay in activation in the left inferior frontal cortex for middle-aged adults was related to PET markers of dopamine synthesis capacity (Landau, Lal, O’Neil, Baker, & Jagust, 2009). This supports the idea that dopamine has a strong effect on functions processed in the prefrontal cortex. The well supported relationship between ageing, dopamine decline and cognitive performance is known as the correlative triad (Bäckman et al., 2006). In short, decline in concentration of dopamine affects both the retrieval and representation of existing knowledge as well as the position of new knowledge. Taking this neurobiological perspective means that loss of knowledge occurs as a consequence of ageing rather than the cause (Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010).

The reason that dopamine has such a large impact on cognitive function is that reduction of this neurotransmitter leads to noisier and therefore less efficient processing in the prefrontal cortex (Bäckman et al., 2010). The way in which this particular process has been successfully modelled in connectionist networks is via alteration of the gain in the sigmoidal transfer function. Effectively, this means changing the slope of the sigmoidal activation function such that the network becomes more susceptible to noise. Further details on how this is applied to the current study are presented in the method section. Such a manipulation has been successfully applied in areas where insufficient or excessive dopamine presence causes abnormal behaviour. For example, increasing the gain function of a three layer recurrent network which was trained on a continuous performance task replicated the performance of human beings who had been provided with methylphenidate, a central nervous system stimulant acting as a dopamine agonist (Servan-Schreiber, Printz, & Cohen, 1990). Further, the continuous performance test and gain adjustment in the transfer function was used to the last two words were used to investigate behavioural deficits in schizophrenics. The results suggested that modelling abnormal dopamine activity can successfully account for the observed impairments in schizophrenic patients when carrying out this task (Braver, Barch, & Cohen, 1999). In the realm of ageing research adjustment, of the gain function was used to capture behavioural observations of memory recall (S.-C. Li et al., 2001). Further, the authors suggest that the decline of dopaminergic neuromodulation relates to less distinctive cortical representations.

Adjustment of the gain parameter in this study is an attractive proposition due both to its validity as a healthy ageing related manipulation as well as a model of decreasing signal-to-noise ratio in Alzheimer’s disease in which the dopaminergic system is also impaired (Lyness, Zarow, & Chui). This factor may contribute to details linked to contextual information and increased sensitivity to interference as well as a decrease in auto associative activities in CA3 of the hippocampus (Savioz, Leuba, Vallet, & Walzer, 2009). The latter observation leading to an impaired ability to detect novel information (Wilson, Gallagher, Eichenbaum, & Tanila, 2006).

4.1.9 Current study

The current study is based on the proposal that inhibition of both lexical and categorical representations is greater in bilinguals due to greater overlap in the representational space. This is evidenced by errors and prolonged reaction time during for bilinguals during recall (Gollan & Acenas, 2004; Gollan et al., 2002) as well as categorical interference (Kroll, 2009). This inhibitory practice over age is ultimately responsible for some aspect of cognitive reserve. As well as taking closer spacing between representations as requirement for increased inhibition, this study will also investigate inhibition within the network by examining the relationship between features of the input set of the network and their influence on the hidden layer.

A prediction, therefore, would relate to the appearance of differences in separation between representations, both lexical and semantic, between neural networks trained to learn one language or two. The bilingual network will show greater clustering of representations as a proxy of inhibition. Furthermore, features of the input set, namely language tags in the second simulation, will provide greater inhibition within the network in order to bias output towards a given language.

This investigation comprises two studies. The first study investigates models of language learning and as such, the development of separate lexical stores. This relates to the established version of bilingual language production in which two lexical stores are connected to a single conceptual store. The second study views the conceptual store as bigger in bilinguals than in monolinguals. This research does not suggest that two completely distinct conceptual stores exist for bilinguals. However, it does assume that differences exist between bilinguals and monolinguals in conceptual or semantic representational storage. Even in compound bilinguals (where an individual learns two languages in the same context where they are used concurrently), while concrete nouns may overlap in conceptual storage, concepts relating to abstract terms may differ (van Hell & de Groot, 1997). For example, the word ‘love’ in English has very different conceptual connotations to the word ‘*amour*’ in French. As such, there will be a significant increase in concepts stored in bilingual individuals compared to monolingual individuals. However, it is worth noting that for coordinate bilinguals who have learnt different languages in different environments, two conceptual systems may exist (Koven, 1998; Pavlenko, 1999).

4.2 Simulation Study I: Language learning network

The aim of this simulation study is to investigate the spacing of lexical representations within monolingual and bilingual neural networks. The motivation for this investigation is the assumption that inhibition of both lexical and categorical representations will be greater in a crowded representational space. Greater recruitment of inhibitory processes would suggest both a bilingual advantage and perhaps the beginnings of CR. The relationship between the lexical representations and the number of languages learned will also be explored over different amounts of biological substrate, as represented by the concept of Brain Reserve (BR). Modelling the neural underpinnings of recruitment of additional inhibitory processes for bilingual speakers outlines this theory and provides some indication of the cognitive and neurobiological beginnings of cognitive reserve.

4.3 Method

4.3.1 Architecture

The models used in this simulation were simple three layer, feedforward back propagating auto-associative neural networks. Two versions were used, a monolingual version and a bilingual version. The input layer had 40 nodes. For each of the two networks, 50 simulants were trained for hidden layer sizes of 5, 10, 15, and 20 nodes (Figure 4.4). The purpose of varying the hidden layer size was to incorporate the general variability in BRC (Stern, 2009) as well as the suggestion that bilinguals have more grey matter than monolinguals (e.g. Abutalebi et al., 2012; Zou et al., 2012). Activation in each node in the hidden layer was calculated according to a hyperbolic tangent sigmoid transfer function. The learning rate was 0.5 and the momentum was fixed at 0.1. The models were implemented in MATLAB and written without the use of toolboxes in order to increase the variety and flexibility of analysis.

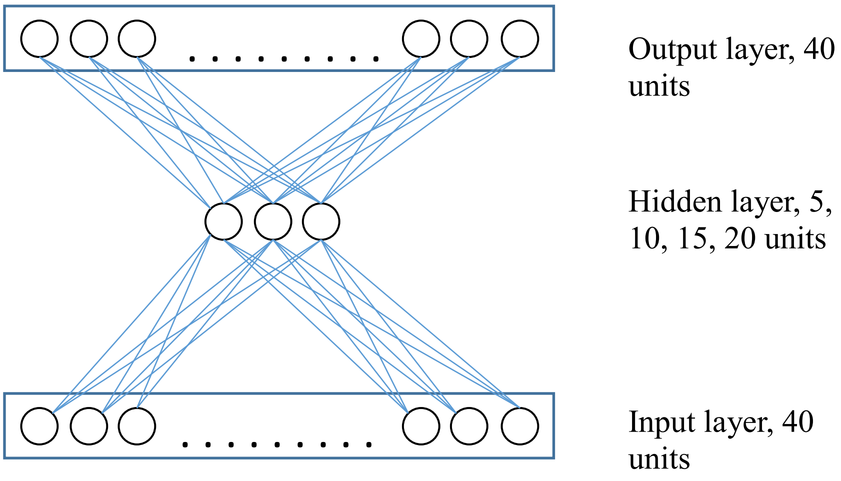


Figure 4.4: Schematic of network used in simulation I. Hidden layer size is varied over four levels.

4.3.2 Training set

Two versions of the language learning model were produced monolingual model concerned with learning a single language and a bilingual model which learned two languages. The Language learned by the monolingual model will be hereafter known as L1 whilst the bilingual model learned L2 in addition to L1. The 'words' used as input were taken from a list of English and Modern Greek phonemes. The English phonemes had already been used in previous study as binary input vectors based on a distributed code of articulatory features (Thomas & Karmiloff-Smith, 2003). Due to similar availability, Modern Greek phonemes were taken from a previously generated data set of thirty four words, also described as a binary vector based on articulatory features (Karaminis & Thomas, 2010). The input vector comprised of 40 digits. L1 made up of a vector of 19 binary digits within each input pattern whilst L2 took up the remaining 21 binary digits.

For the bilingual model, a joint input procedure was used in which L1 and L2 were presented to the model at the same time to represent a compound bilingual environment. In the monolingual network, the input nodes reflecting the second language were not activated during training.

4.3.3 Training

Batch training was carried out in which weight changes are accumulated over presentation of the entire dataset prior to being applied. This differs from on-line updating in which weights are updated after presentation of a single *instance*, in this case the presentation of a single word at input and output. It is supposed that a weight change that takes into account all instances of data at one time presents a more ‘correct’ picture of the error gradient (Wilson & Martinez, 2003).

Both networks were trained for a total of 1000 epochs. This was more than sufficient for the error to achieve asymptote. For the monolingual network, the error curve asymptoted at around 120 epochs. As mentioned previously, four versions of both the monolingual and bilingual network were trained. Each version had a different size hidden layer. For each of the hidden layer sizes in both monolingual and bilingual networks, 50 simulants were used, each with a randomised seed for the weights between nodes at the beginning of training.

The bilingual network reached asymptosis at around 200 epochs for all hidden layer sizes. Unsurprisingly, the error at this point decreased in line with the amount of nodes in the hidden layer. Continued training did demonstrate a gradual decrease in error past this point. L1 and L2 separately showed a gradual decline in performance past asymptote. This is likely because of over-fitting of the training data beyond the initial asymptotic point.

4.4 Analysis and Results

Analysis for the language learning network was carried out to investigate two aspects of representational distribution. Firstly, in accordance with previous models of bilingual language recognition (e.g. SOMBIP and BSRN), separations between the two languages were explored. Secondly, the analyses took representational spacing further and explored the distribution of representations within L1 in both monolingual and bilingual networks.

When each word was presented to the network, a vector of activation was produced across all of the hidden units of the network. This vector related to a point in multi-dimensional space with five nodes in the hidden layer relating to five dimensions, ten nodes relating to ten dimensions etc. This therefore meant that the clustering of the words in each language could also demonstrated measuring distances between the points representing the words within and between each language. Representation of the distances between the words was carried out by the production of a heatmap (Figure 4.5). The heatmap plotted the two languages against each other with the colour at the point at the intersection of the two languages relating to the distance between them. The darker the colour at the point of intersection, the greater the distance between them. The visualisation revealed some clustering in each language. As the amount of nodes in the hidden layers increases, the two languages polarise with the areas representing distances between L1 and L2 words becoming darker. The greater clustering of words within L2 was demonstrated in the five node hidden layer network with greater patches of white in the points at which the words from the two languages intersected. Such clustering may be the result of a more consistent structure within the L2. Overall, both languages visually demonstrated greater darkening at points within and between themselves as hidden layer size increased. This suggested a general increase in spacing or de-clustering or words in relation to the larger amount of substrate available.

4.4.1 Language separation

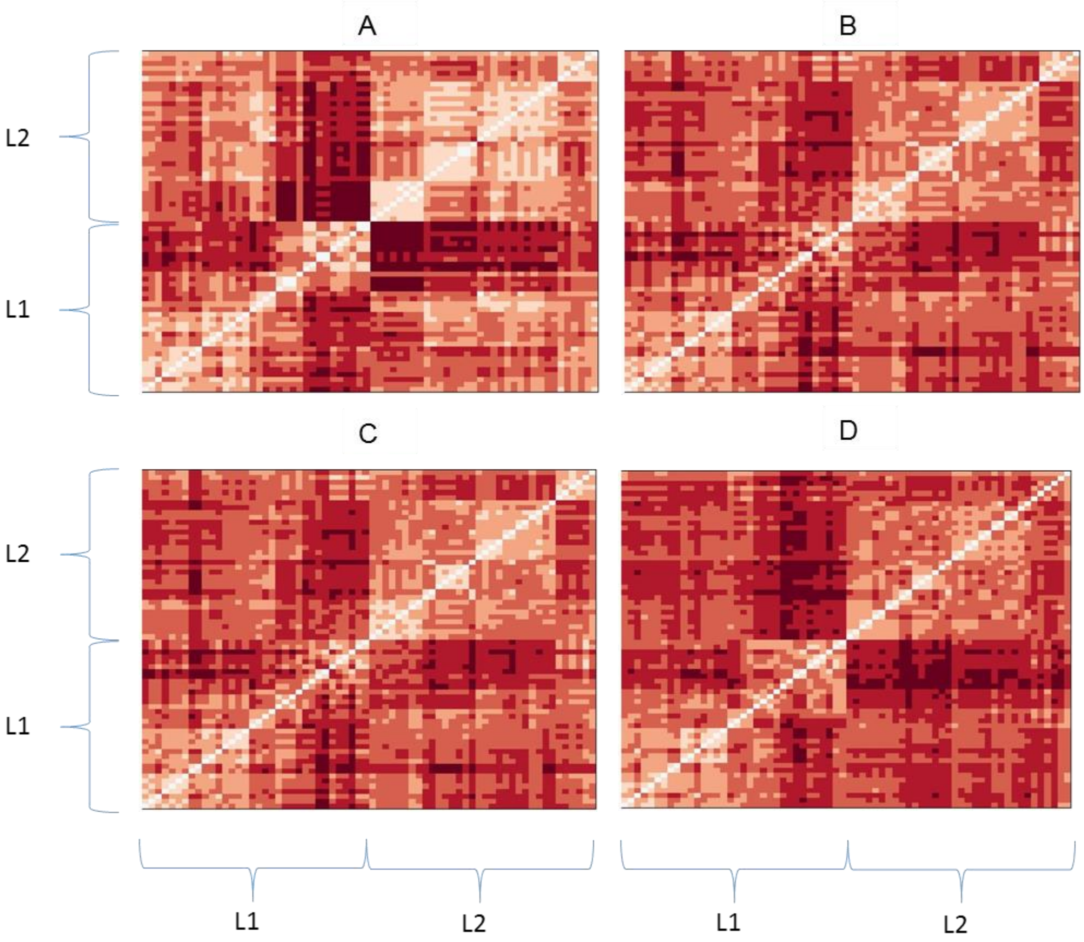


Figure 4.5: Heatmaps at four hidden layer sizes (A -5, B -10. C-15, D-20). Squares within each heatmap represent the relative distance between the two words in representational space. The darker the colour the larger the distance.

For a visualisation of the distribution of representations and the separation of languages L1 and L2 of the bilingual network, multidimentional scaling was applied to the activation profiles of the hidden layer of the bilingual network in response to presentation of ‘words’ in both languages (Figure 4.6). The scatterplots demonstrate increased separation between both languages over increased hidden layer size as well as some increased separation of representations within the languages themselves. From this perspective, it appeared that with the greater the amount of BR, represented by hidden layers, there was less overlapping between representations. Following on from the idea of retrieval induced inhibition, this would point to a lesser need to inhibit to retrieve representations. The following section compares the distribution of representations within L1 between both monolingual and bilingual networks in more detail.

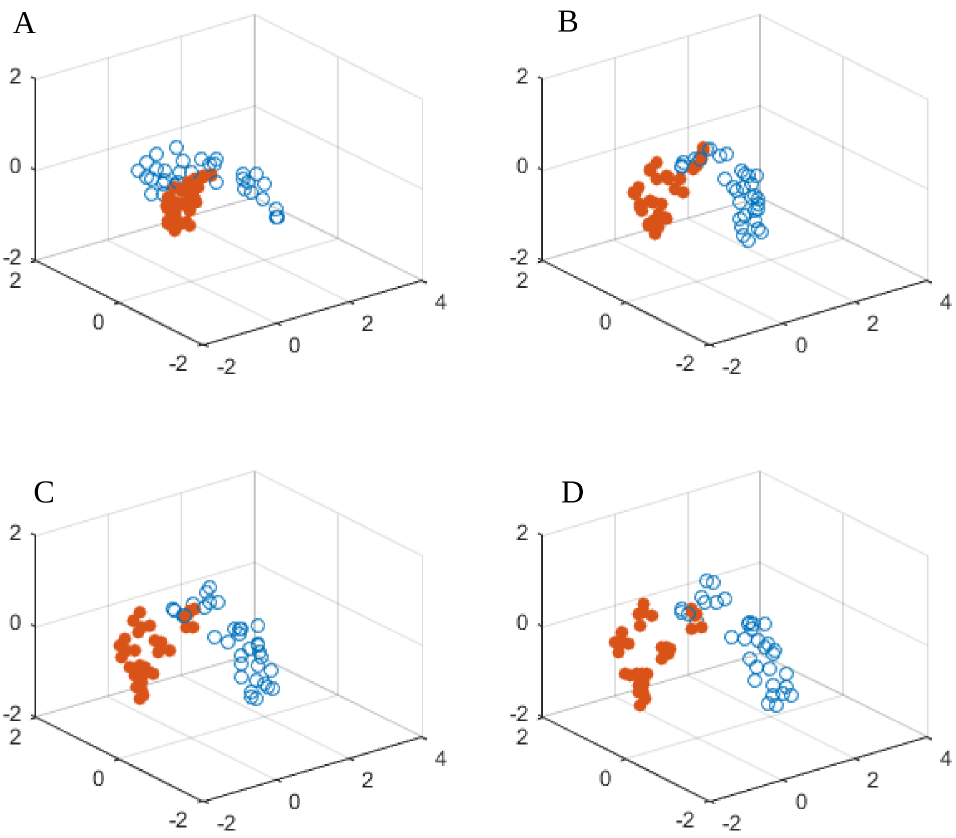


Figure 4.6: Scatterplots demonstrating distribution of lexical representations for both languages within the bilingual network at 200 epochs averaged over 50 simulants. L1 is represented by blue circles and L2 is represented by red circles. A, B, C, & D relates to hidden layer sizes 5, 10, 15, and 20 respectively.

4.4.2 Representational spacing within L1

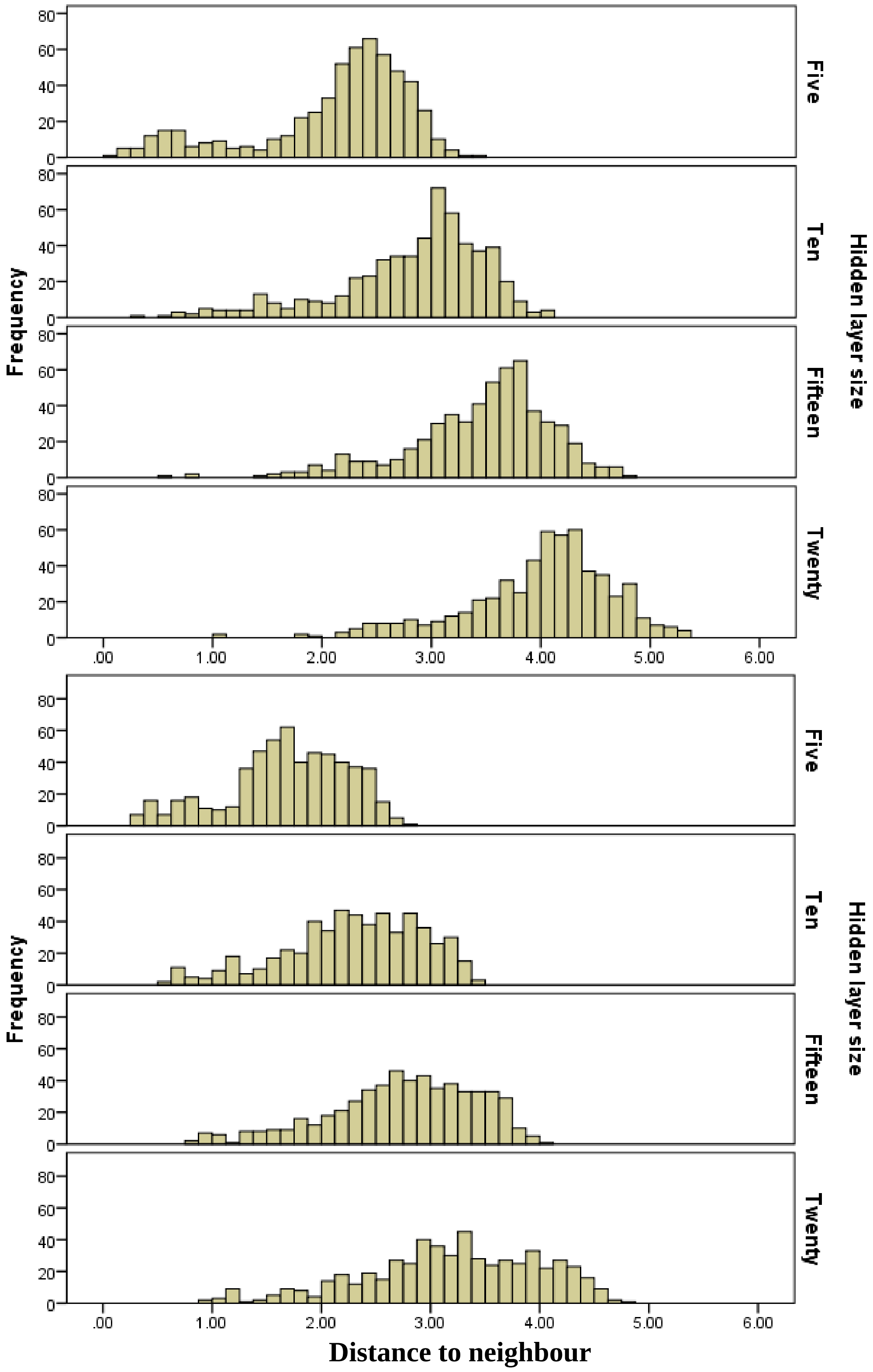
In order to compare monolingual and bilingual networks, the single language used by the monolingual network as well as L1 of the bilingual network. To address the question as to the separation of representations within a single language, two methods were used. In this initial analysis, the sum of the total Euclidean distances among lexical representations in L1 were compared between monolingual and bilingual networks.

At 200 epochs, the earliest point at which both monolingual and bilingual networks were at asymptote, histograms were produced showing the distance from each of the words in L1 all of its neighbours (Figure 4.7). This was also plotted for each of the hidden layer sizes. The descriptive statistics also represented the mean and standard deviation of all distances reflected in the histograms (Figure 4.7).

Table 4.1: Mean (SD) of the distance between each word and its neighbours in L1 for monolingual and bilingual networks.

	Hidden layer size			
	Five	Ten	Fifteen	Twenty
Monolingual	1.70 (.57)	2.27 (.62)	2.73 (.68)	3.24 (.85)
Bilingual	1.51 (.52)	1.98 (.71)	2.36 (.65)	2.78(.73)

An ANOVA was carried out on the Euclidean distances between activation profiles for each word of L1 for both monolingual and bilingual networks over all four levels of hidden layer size. The ANOVA demonstrated a main effect for network type, whether L1 was from a monolingual or bilingual network (F (1,4480) = 281.83, p<.001, η^2 = .06), a main effect for hidden layer size (F (3,4480) = 921.89, p<.001, η^2 = .38), and an interaction between network type and hidden layer size (F (3,4480) = 8.52, p<.001, η^2 = .01). The interaction was due to divergence of the two network types as the number of hidden units increased. The spacing between representations continued to increase for both monolingual and bilingual networks but this trend reduced over higher levels of hidden layer size for the bilingual model. A post hoc analysis using Bonferroni adjustment demonstrated significant comparisons between all levels of hidden layer size (p<.001). This significant effect continued when the monolingual and bilingual networks were analysed separately.



4.7: Histograms of distances between each word in L1 and the rest of the L1 lexicon for the monolingual (top) and bilingual (bottom) networks. For each word in L1, distances are averaged over 50 simulants.

To further investigate the distribution of representations within L1, multidimensional scaling was applied to the activation profiles of the nodes in the hidden layer gained in response to the presentation of each word to the monolingual network. The first three dimensions were used in response to each word of L1 for the monolingual network (Figure 4.8). In comparison to Figure 4.6, greater distribution of representations within L1 can be observed.

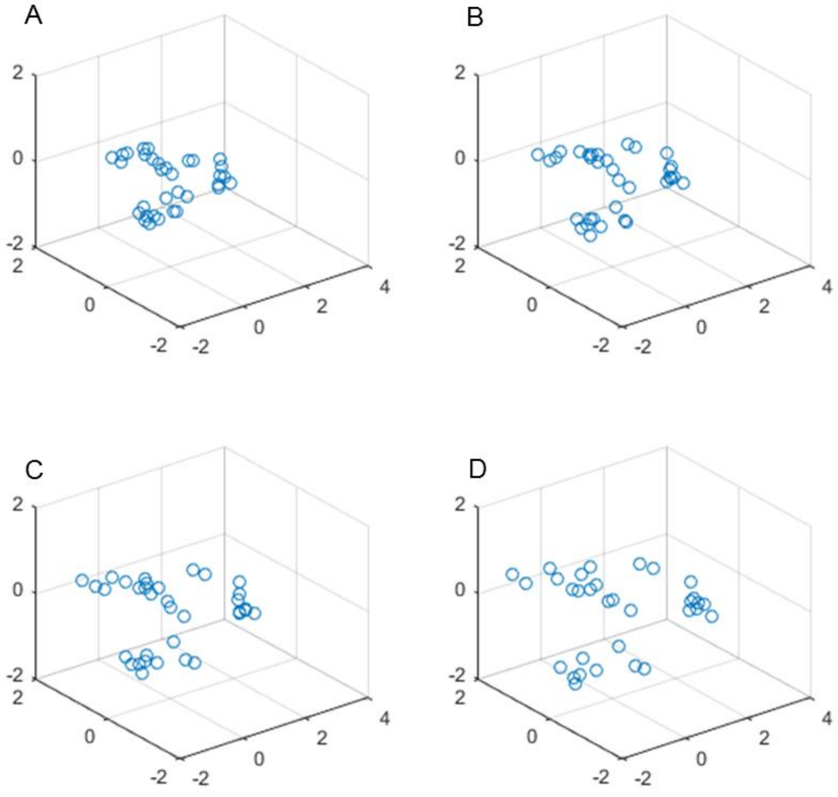


Figure 4.8: Scatterplot demonstrating distribution of lexical representations for the monolingual network after 200 epochs averaged over 50 simulants. Each circle is a single word. A, B, C, & D relates to hidden layer sizes 5, 10, 15, and 20 respectively.

Comparison of both sets of scatterplots appeared to show that the constraints placed on the bilingual network by the inclusion of an additional language did produce greater clustering among representations and a clear separation between languages. As with the results from the ANOVA, spacing between representations increased with the amount of available space, represented by the amount of nodes in the hidden layer, as a proxy of BR.

4.5 Discussion

The models in the first part of this chapter were created to examine how representations in monolingual and bilingual networks distributed themselves. The models explored in this first simulation provided a snapshot of representational spacing for the words learned very close to the point of asymptote of both networks. The monolingual network learned to auto-associate words from a single language (L1) whilst the bilingual network did the same with two languages (L1 and L2). Using the activation vectors of the hidden layer in response to each word, both the monolingual and bilingual networks were compared. Results show that representations in the bilingual network appearing more clustered as indicated by lower overall Euclidean distances demonstrated by the histogram. Scatterplots based on multidimensional scaling of the activation profile in response to presentation of the words from L1 and L2 demonstrated a trend towards greater clustering for representations in the bilingual network. The ANOVA revealed a significant interaction between whether the network learned one or two languages and the amount of nodes in the hidden layer in terms of the Euclidean distances between representations in each of the networks for L1. Whilst the representations in the monolingual network were more spaced out, both network types showed increased spacing between representations as the hidden layer size grew. However, as the amount of nodes in hidden layers increased in the bilingual network the advantage gained from the additional space did not match that of the monolingual network. This may be due to an increasing separation of the languages as a whole leaving a more clustered L1 with demand increasingly outstripping supply in terms of representational space within which to move.

The results from the scatterplots from the bilingual model demonstrated that even without the use of specific tags, the network will separate languages based on their characteristics. This occurrence may be due to the distinct characteristics of the two languages used with L2 being more populated in terms of articulatory features as well as containing two additional categories. Whilst it was not intentional to produce language tags for separation of languages, the additional categories of articulatory features which were active in some of the ‘words’ of L2 may have carried out the same function since these would only have been available to the second language. This finding may have repercussions in relation to the second part of the study in terms of representational overlap being a feature which contributes to cognitive reserve via retrieval based inhibition.

The results of this study support the BSRN and the SOMBIP models in that the current simulation also demonstrates that separation between representations belonging to a particular category can occur based purely on differences within the feature set. In the SOMBIP model, it was the reliance of phonological upon phonological cues. What these models and the current simulation have in common is that aspects of the input languages are sufficient to delineate them. For the BSRN model, co-variation regularities of the word associations were the cues which allowed for language separation. To be able to do this, structure was simulated at the level of the sentence with words from the same language belonging to the same sentence. As with the current simulation, the differences were manifested by overall activation patterns for each language. What is interesting to note in the BSRN model was that simulating brain trauma by the removal of nodes in the hidden layer revealed that some single nodes accounted for large amounts of the difference between each language. For example, a single node in the network accounted for 27% of the difference whereas the average contribution of nodes in hidden layer was about 3%. This may suggest some inhibitory action built into the network activity with individual nodes providing a greater influence as to whether nodes in the subsequent layer are activated or not. This aspect is investigated in the second simulation.

The current simulation explored the spacing between lexical representations for monolingual and bilingual networks. The results demonstrated that L1 lexical representations in a bilingual network are more clustered over all levels of BR, represented by hidden layer size, than in a monolingual network. The following section describes how this may relate to increased inhibition in a bilingual network as well as simulating the distribution of representations over age.

4.6 Simulation study II: Picture Naming

The simulation in this part of the chapter builds upon the findings of the previous simulation within which differences were found in representational spacing between monolingual and bilingual networks trained to learn one or two languages (both languages involved in this study are hereafter known as L1 and L2). The aim of the current study is to further investigate the distribution of representations at a conceptual level whilst taking a longitudinal perspective by including a representation of age-related decline in dopamine in the simulation (Bäckman et al., 2010). In looking at representations between categories within a single language, this study also aims to investigate the source of any language related disadvantages in bilinguals. For example, lower performance in picture naming tasks (Gollan, Montoya, Fennema-Notestine, & Morris, 2005; Roberts, Garcia, Desrochers, & Hernandez, 2002).

4.6.1 Architecture

The models used in this study were simple three layer, feedforward back propagating neural networks. Two versions were used, a monolingual version and a bilingual version. The input layer was 26 nodes and the output layer was 40 nodes (Figure 4.9). For each of the two networks, 50 simulants were trained for hidden layer sizes of 5, 10, 15, and 20 nodes. The purpose of varying the hidden layer size was to represent the variability in BR (Stern, 2009). The learning rate was 0.5 and the momentum was fixed at 0.1.

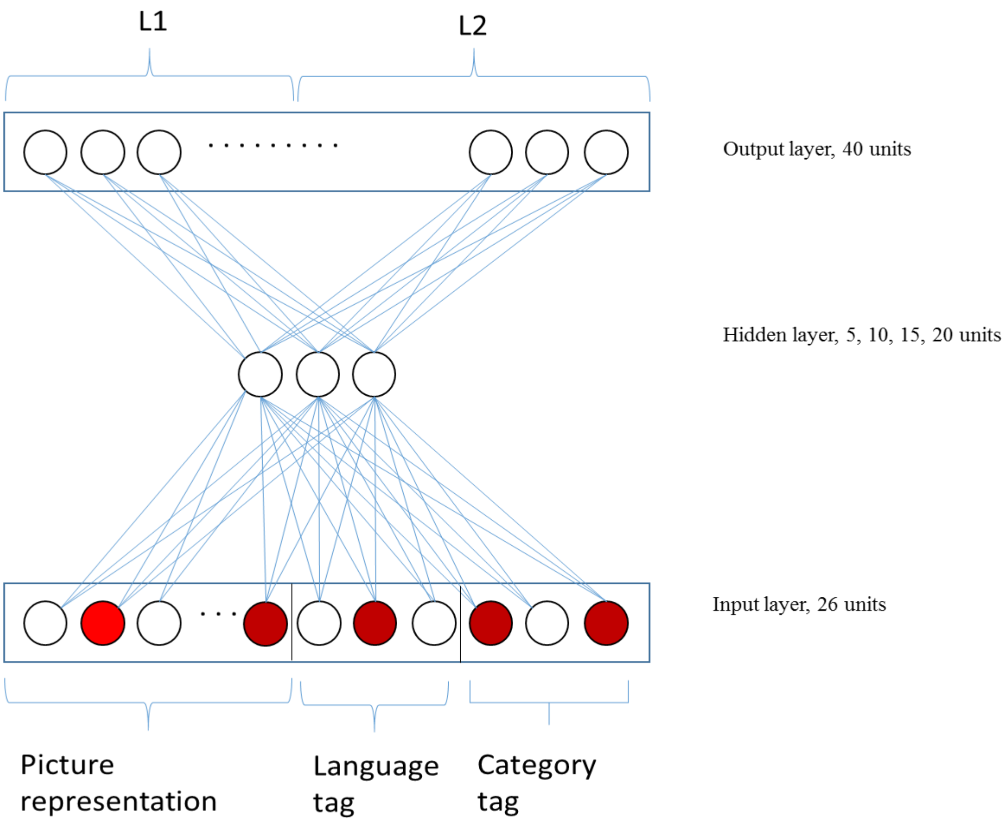


Figure 4.9: Schematic of network used in simulation II. Hidden layer size is varied over four levels.

4.6.2 Training set

As the focus of this study was the representations within the hidden layer rather than specific task performance, a compromise between an artificial language and a realistic corpus was used for input. The inputs used in both models were patterns of 26 binary digits. The first 20 digits were randomised to control for similarity between representations. The next three binary digits represented a language tag which represented the language which the picture should be encoded in. This was added to guarantee separation of the two sets of pictures in the bilingual model since the rest of the input consisted of a random pattern. The final three binary digits of each input presentation related to the membership of a semantic category, for example, living versus nonliving objects (Figure 4.10).

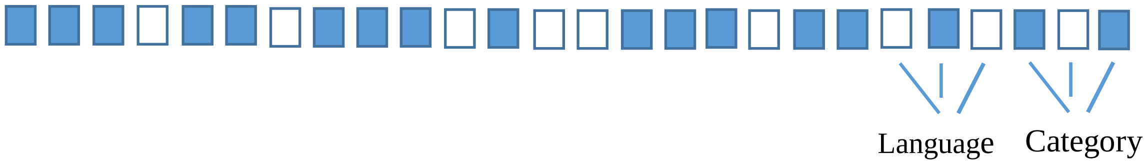


Figure 4.10: Example of a single binary input vector representing one picture. Tags for language and category at the end of the input vector each take two forms to represent membership of one of two languages, L1 and L2 and one of two categories, A and B.

34 input patterns were used in the monolingual model. With the exception of changes made to the language and category tags, the bilingual input set was augmented with a further identical 34 input patterns for the bilingual model, making 68 in total for the bilingual model. Within L1 for the monolingual network and within L1 and L2 for the bilingual network, further division was created by coding the category tags to represent one of two fictitious categories, A and B, of which there were seventeen of each in each language. L1 was represented by the tag ‘010’ with L2 being represented by ‘101’. Within the languages, category A was represented by ‘101’ and category B by ‘010’. The output ‘words’ used for the monolingual were single phonemes from a dataset of English phonemes which had been converted to a binary input set using a set of 19 features (Thomas & Karmiloff-Smith, 2003). The output set for the monolingual network were taken from the previous simulation and comprised of 34 English words with a further 34 Modern Greek words produced for the bilingual model. The English words (known as L1)

were used both in the monolingual and bilingual model and the Modern Greek words represented the second language in the bilingual model (known as L2). In the monolingual model, the first 19 nodes in each output pattern were taken up by a representation of L1 whilst the rest of the nodes in each pattern were left at zero. This set of output patterns was the same for the first 34 output patterns in the bilingual model. However, a further 34 output vectors were added for which the first 19 nodes were set to zero and the remaining 21 nodes represented L2. It is important to note that even though existing features were used, the arbitrary relationship between meanings and names was maintained due to the randomised input vectors representing pictures.

4.6.3 Training

Both networks were initially trained for 800 epochs. The starting weights for each was seeded randomly from a uniform distribution of between 0 and 1. Training for both networks took around 200 epochs for the error to reach an asymptotic state. For comparison, test data was introduced to both monolingual and bilingual networks in the form of both categories of L1 only. Overall, error settled at a slightly higher level in the bilingual network. This can be attributed to the increase in constraints in the bilingual network as it needed to accommodate the same amount of ‘pictures’ as the monolingual network but in both languages. Given that an asymptotic state was achieved around 200 epochs, it was decided that at 220 epochs the network was considered mature for the purposes of analysis and interventions. Therefore, it was at this point that dopamine decline was initiated by decreasing the gain of the sigmoidal transfer function closer to zero by steps of 0.0015 at each epoch. However, back propagating to learning still continued after 220 epochs. Equation 2 shows the transfer function where y is the output calculated from the activation (a), h is the threshold and k is the gain.

$$y = f(a) = \frac{1}{1+e^{-k(a-h)}} \qquad [2]$$

Changing the gain to gradually approach zero reduces the steepness of the sigmoid function and as such makes the nodes in the hidden layer of the neural network in question increasingly less responsive to changes in the input. As such, this manipulation reflects the effects of reduced catecholamine effectiveness over age and the subsequent cognitive effect of decreased ability to detect a signal embedded in noise (Li, Lindenberger, & Sikström, 2001; Servan-Schreiber, Printz, & Cohen, 1990).

4.7 Analysis and results

As with the previous part of this study, multidimensional scaling was applied to the activation profile of the hidden layer for both monolingual and bilingual networks at asymptote. This was only applied to both semantic categories A and B in L1 for each of the network types. The purpose of this analysis was to observe any differences in spacing between representations in the single language within either of the categories. Representational spacing was investigated by calculating the sum of distances between representations. This was then calculated at each epoch to investigate the development of representational spacing over the training span.

To complete the investigation of spacing between representations, the separation of categories within L1 were calculated between monolingual and bilingual models. To this end, an F-value was calculated. Euclidean distances were calculated to all representations within L1. Further, distances to the representations within categories A and B were also calculated. This provided a measure of within and between categories distances, from which an F-value was calculated. It is worthy of note at this point that although the metric is similar to a F-statistic, no statistics can be carried out with his value based on an F-distribution. Instead, the metric was used to track longitudinal changes in representational separation. The F-value was also calculated in line at each epoch of training. Finally, an investigation into whether the network was monolingual or bilingual as well as the amount of nodes in the hidden layer over time were significantly contributing factors to predicting the separation of representations into categories were investigated with a multilevel model.

4.7.1 Separation of representations within language

The Euclidean distances from each representation to its neighbours was calculated for categories A and B of L1 for both the monolingual and bilingual networks (Table 4.2).

Table 4.2: Means (SD) of Euclidean distances for L1 of monolingual and bilingual networks from each word to its neighbour for categories A and B.

		Hidden layer size			
	Category	**Five**	**Ten**	**Fifteen**	**Twenty**
Monolingual	**A**	0.60 (0.12)	0.89 (0.19)	1.11 (0.24)	1.30 (0.28)
	B	0.77 (0.15)	1.12 (0.22)	1.37 (0.26)	1.59 (0.30)
Bilingual	**A**	0.38 (0.11)	0.58 (0.14)	0.76 (0.16)	0.91 (0.19)
	B	0.56 (0.21)	0.75 (0.23)	0.94 (0.25)	1.09 (0.24)

An ANOVA carried out on category A distances only revealed significant main effects for both network type , either monolingual and bilingual (F (1,1080) = 765.97, p<.001), and hidden layer size (F (3,1080) = 545.19, p<.001). Furthermore, a significant interaction between network type and hidden layer size was also observed (F (3,1080) = 11.03, p<.001). This was due to a very similar divergence of scores to the first simulation since distances between representations for both monolingual and bilingual increased over larger hidden layer sizes but the representations in the monolingual network had spread out to an increased degree.

For categories A and B of L1 the results of multidimensional scaling of the activity profiles of hidden layers were plotted for the monolingual and bilingual networks (Figure 4.11 and Figure 4.12). This was carried out to illustrate any differences of semantic storage in representational space. With increasing hidden layer size, the representations within a category are more spread out. However, overall the effect appears greater with the monolingual model. Conversely, clustering of representations within the hidden layer of the bilingual model is tighter. This was also reflected by the development of representational spacing of a single category from L1 in both monolingual and bilingual networks carried out over the period of training (figure 4.15).

Table 4.2: Means (SD) of Euclidean distances for L1 of monolingual and bilingual networks from each word to its neighbour for categories A and B.

		Hidden Layer Size			
	Category	**Five**	**Ten**	**Fifteen**	**Twenty**
Monolingual	**A**	0.60 (0.12)	0.89 (0.19)	1.11 (0.24)	1.30 (0.28)
	B	0.77 (0.15)	1.12 (0.22)	1.37 (0.26)	1.59 (0.30)
Bilingual	**A**	0.38 (0.11)	0.58 (0.14)	0.76 (0.16)	0.91 (0.19)
	B	0.56 (0.21)	0.75 (0.23)	0.94 (0.25)	1.09 (0.24)

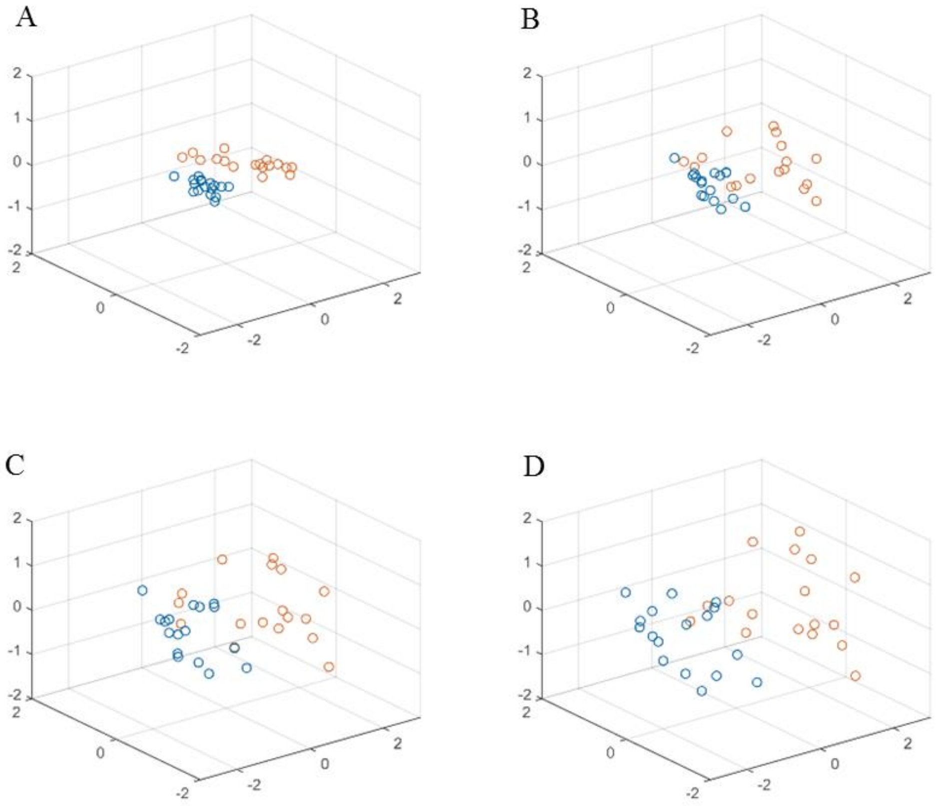


Figure 4.11: Scatterplots representing the distributions of representations of categories A and B within L1 of the monolingual network at 220 epochs. Each graph refers to hidden layer sizes of five (A), ten (B), fifteen (C) and twenty (D) nodes. The blue dots relate to category A and the red dots relate to picture representations in category B.

The dispersal of representations from a calculated centroid for category A only was plotted over the life span of the network (Figure 4.13). Higher hidden layer size networks showed the greatest spacing between representations with the greatest dispersal demonstrated by the representations within the higher hidden layer sizes of the monolingual network. At 220 epochs the plot shows that a reduction in gain in the transfer function as a proxy of age starts a trend towards a clustering of representations within that category. This appears to be the case for both network types and all of the hidden layers. Importantly, the error of the networks remained close to zero whilst increased clustering of representations occurs as a result of the ageing of the networks.

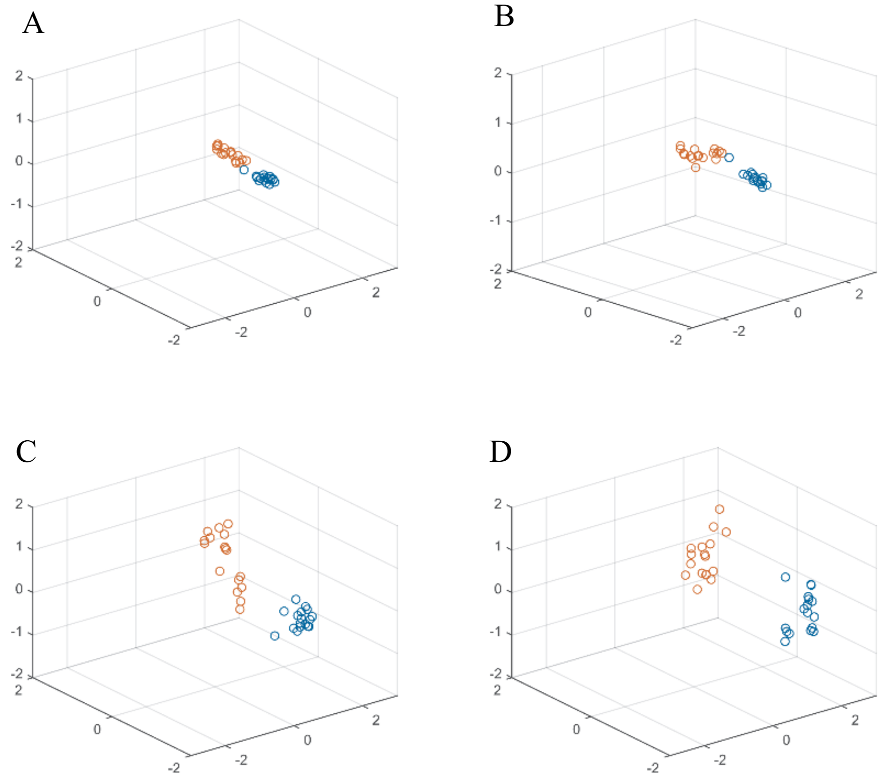


Figure 4.12: Scatterplots representing the distributions of representations of categories A and B within L1 of the bilingual network at 220 epochs. Each graph refers to hidden layer sizes of five (A), ten (B), fifteen (C) and twenty (D) nodes. The blue dots relate to category A and the red dots relate to picture representations in category B.

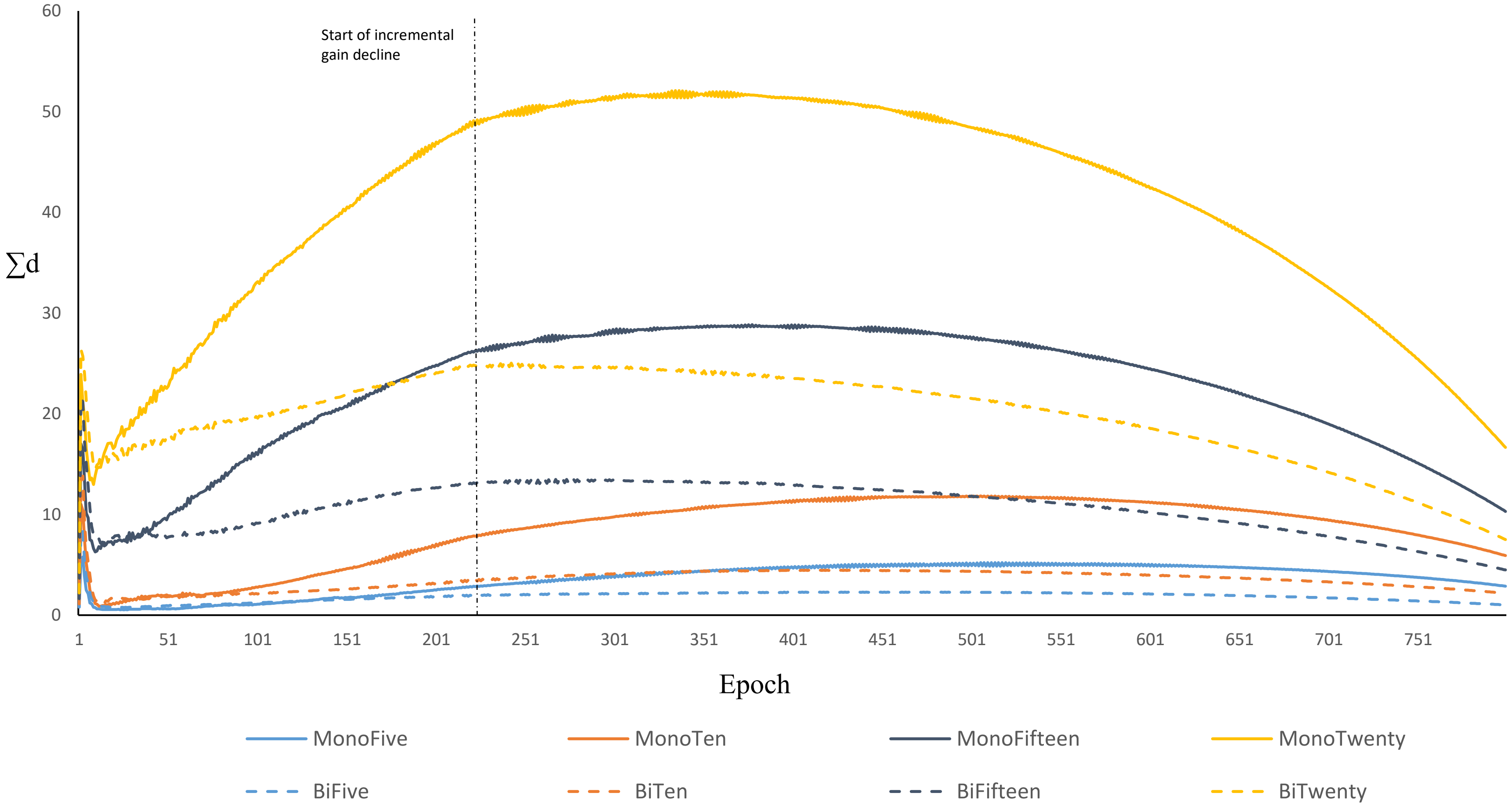


Figure 4.13: Line graph demonstrating the longitudinal change of the sum of the distances for category A within monolingual and bilingual models over all hidden layer sizes. Lines represent mean score of 50 simulants. Dotted lines represent bilingual projections, solid lines represent monolingual projections. Different colours relate to the four hidden layer sizes.

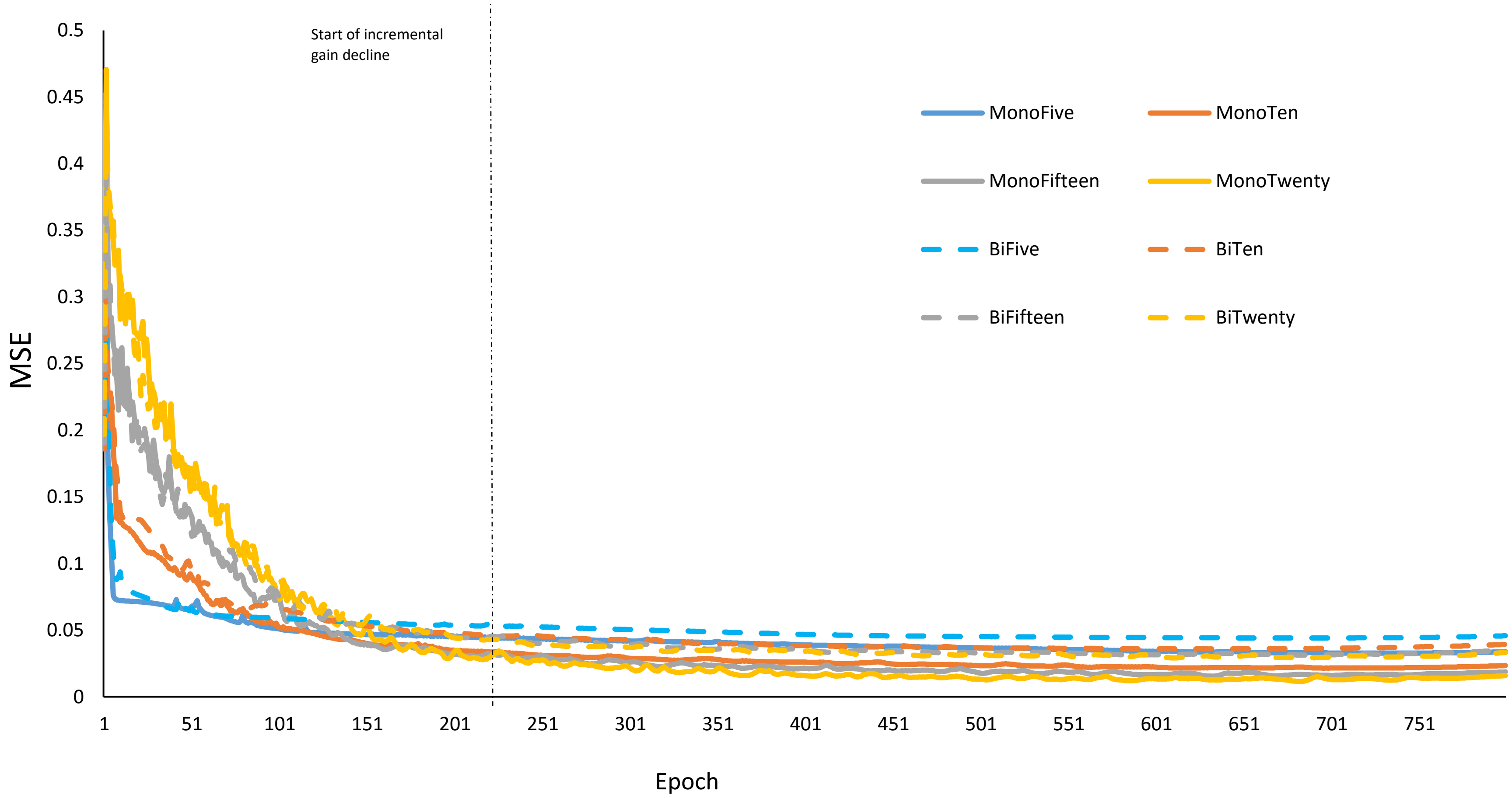


Figure 4.14: Training progression of all networks, measured by mean squared error (MSE).

4.7.2 Separation of semantic categories

In addition to the progression of the overall separation of the categories within LI for both monolingual and bilingual networks, plots were created to illustrate the nature of the separation between and within the categories. This included a longitudinal plot of the F-value as a representation of the separation between and within categories of L1 (Figure 4.15). As contributing factors to be calculated F-value and worthy of inspection in their own right, plots were also produced of the MSE within categories (Figure 4.17) and MSE between categories (Figure 4.19) as measures of representational spacing within and between the categories respectively. Furthermore, a bootstrapped null distribution of Euclidean distances was created for each network type and hidden layer size. This allowed a p-value to be calculated. Doing so provided a way of controlling for hidden layer size since comparison was made between a null with the same amount of hidden layers rather than each of the other hidden layer sizes. This then provided the opportunity to investigate the individual effects of hidden layer size (Figure 4.16, Figure 4.18, & Figure 4.20).

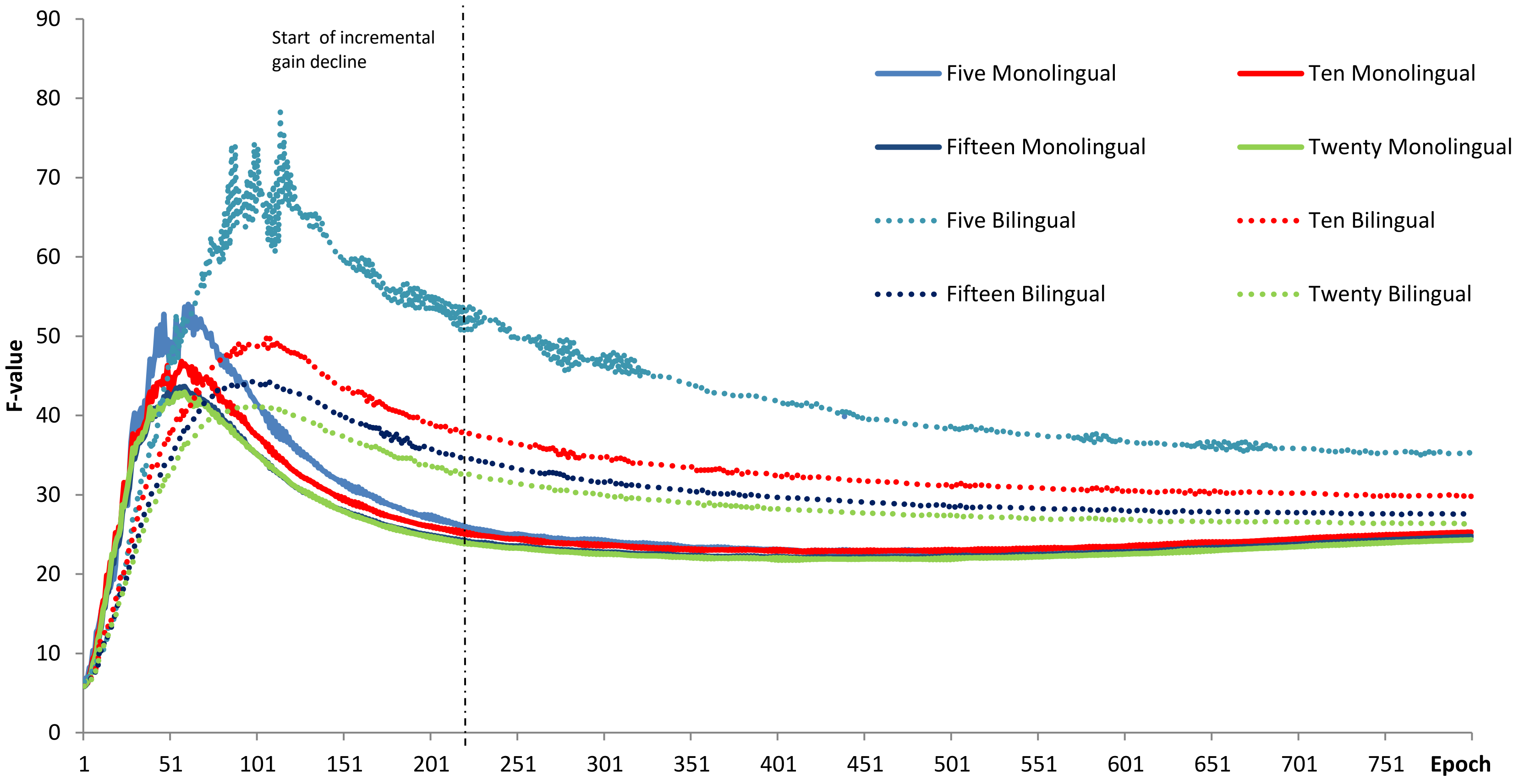


Figure 4.15: Projections of F-values reflecting separation between semantic categories in both models overall all hidden layer sizes. Dotted lines represent bilingual projections, solid lines represent monolingual projections. Different colours relate to the four hidden layer sizes.

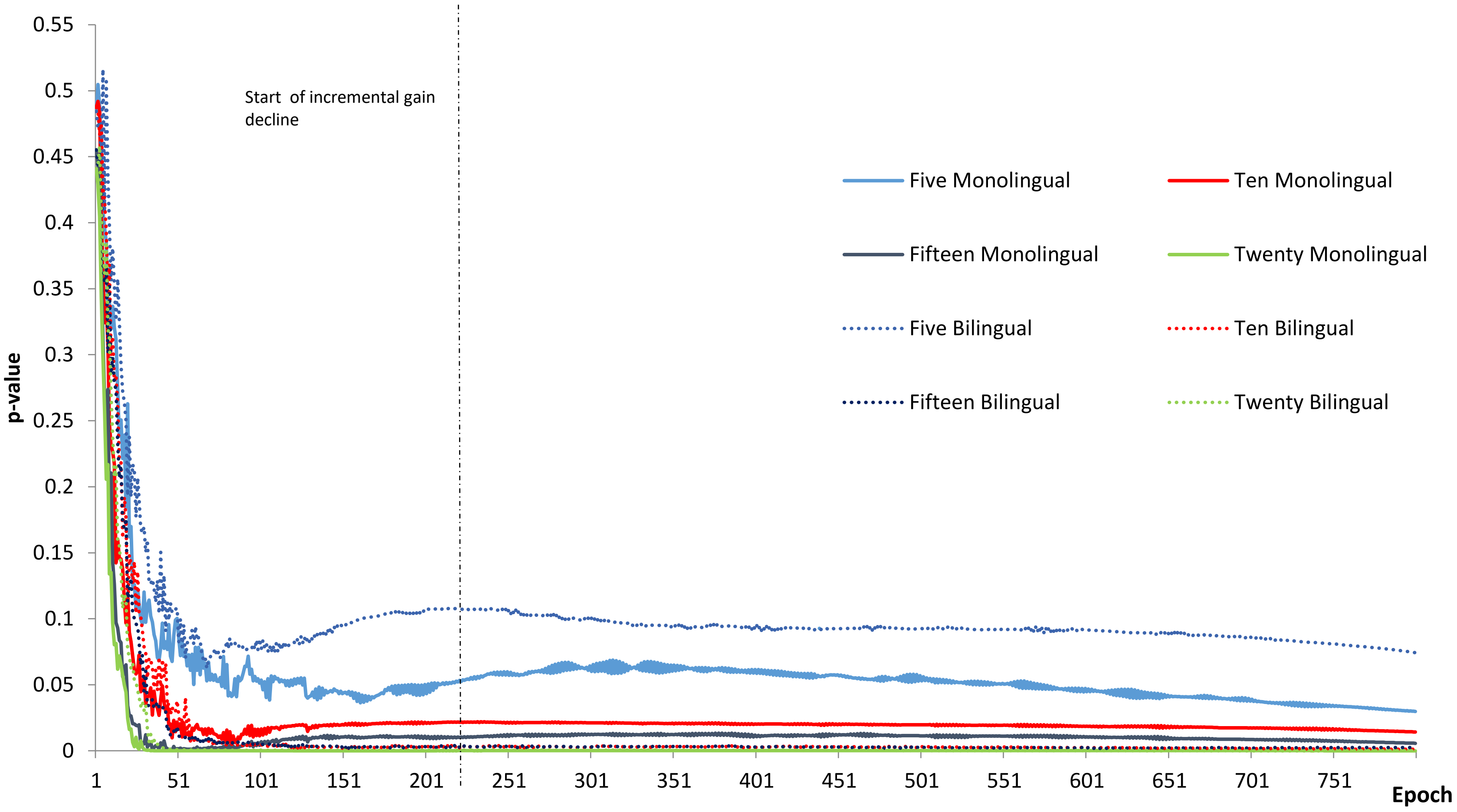


Figure 4.16: p-values representing significance of category separation when compared to a null distribution of representations, plotted over lifespan of monolingual and bilingual networks for all hidden layer sizes.

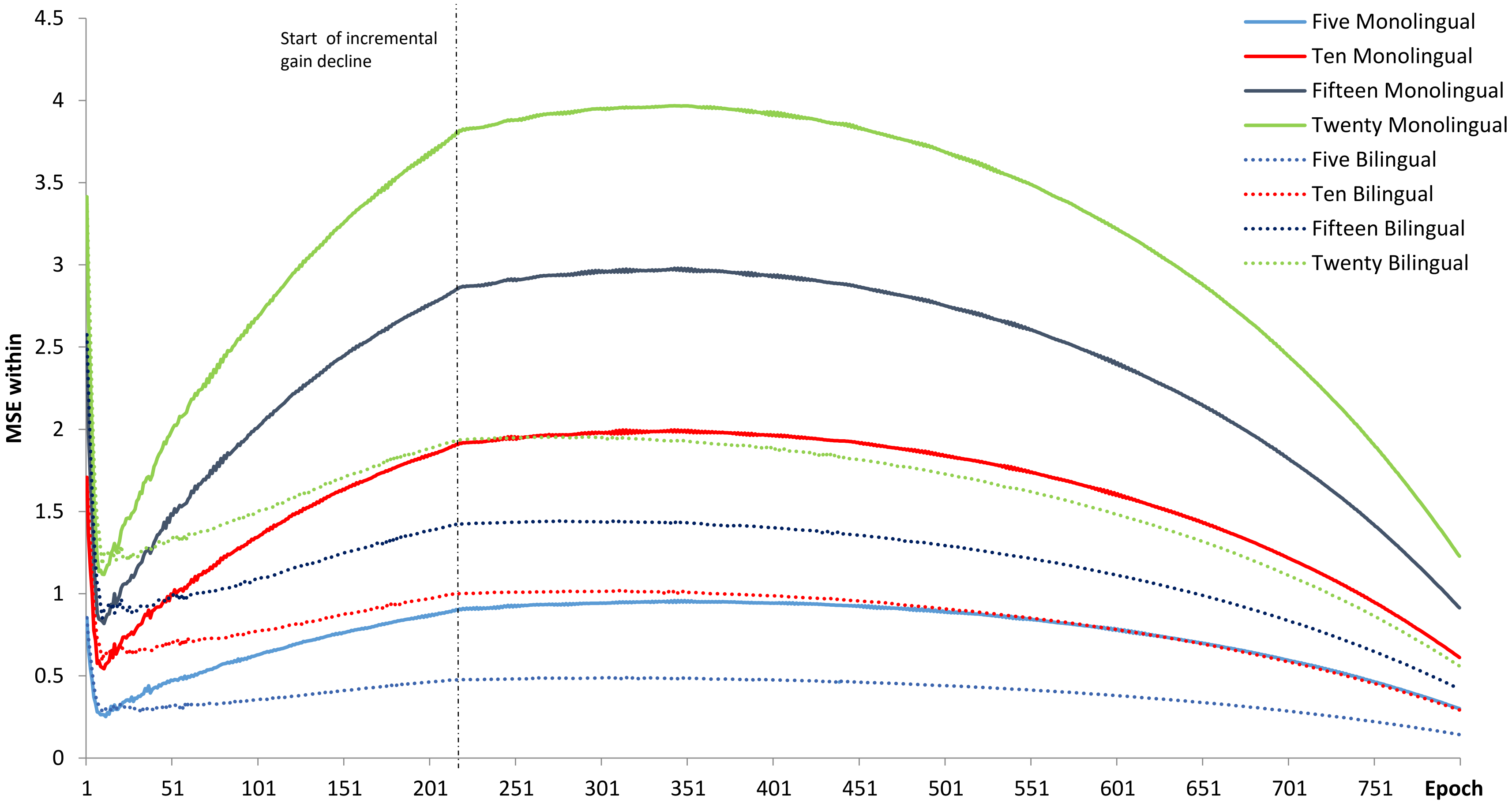


Figure 4.17: Projections of MSE values representing the within category representational spacing. Values plotted over lifespan of monolingual and bilingual networks for all hidden layer sizes.

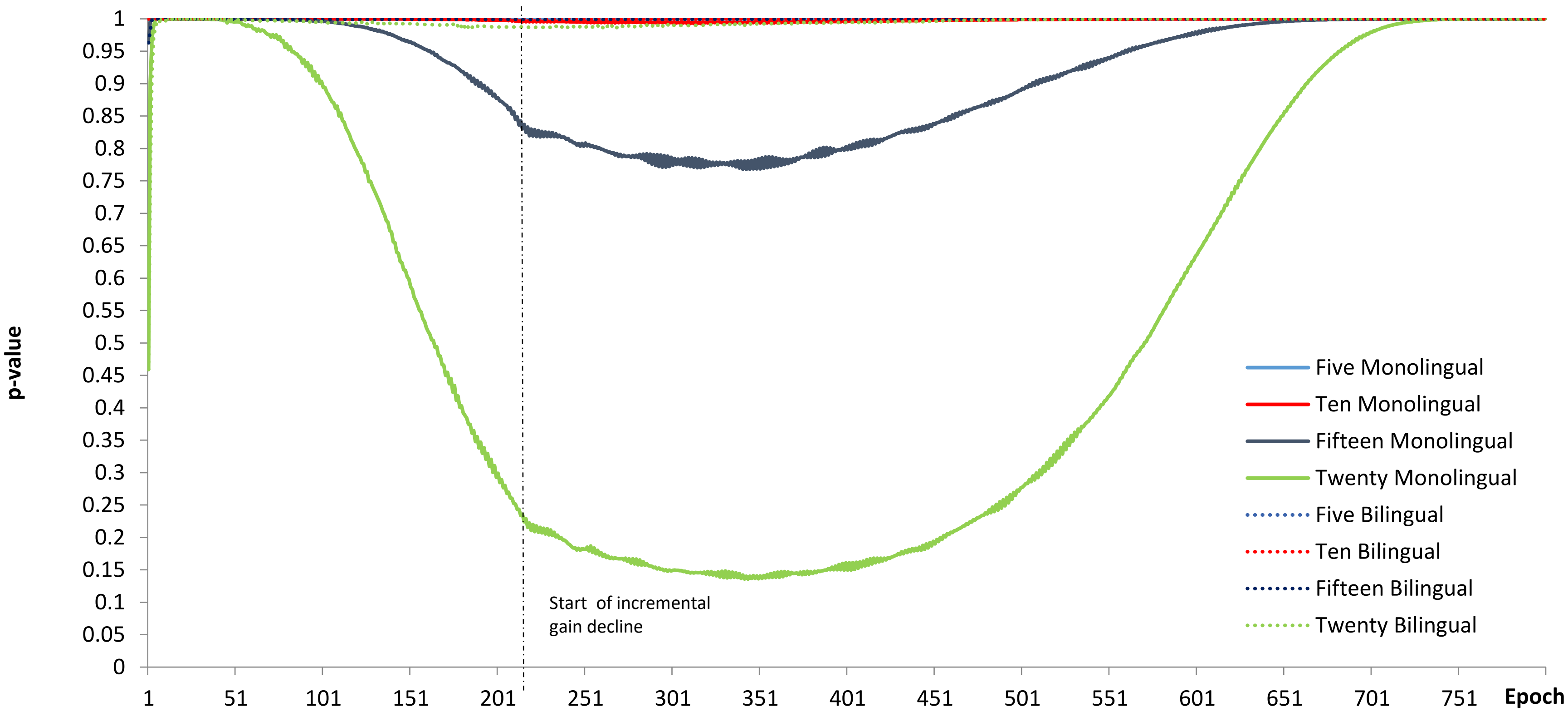


Figure 4.18: p-values representing significance of spreading of categories (p<0.5 = significant reduction in spacing (clustering), p>.95 = significant increase in spacing) of within category representations when compared to null distribution of the same. Values plotted over lifespan of monolingual and bilingual networks for all hidden layer sizes.

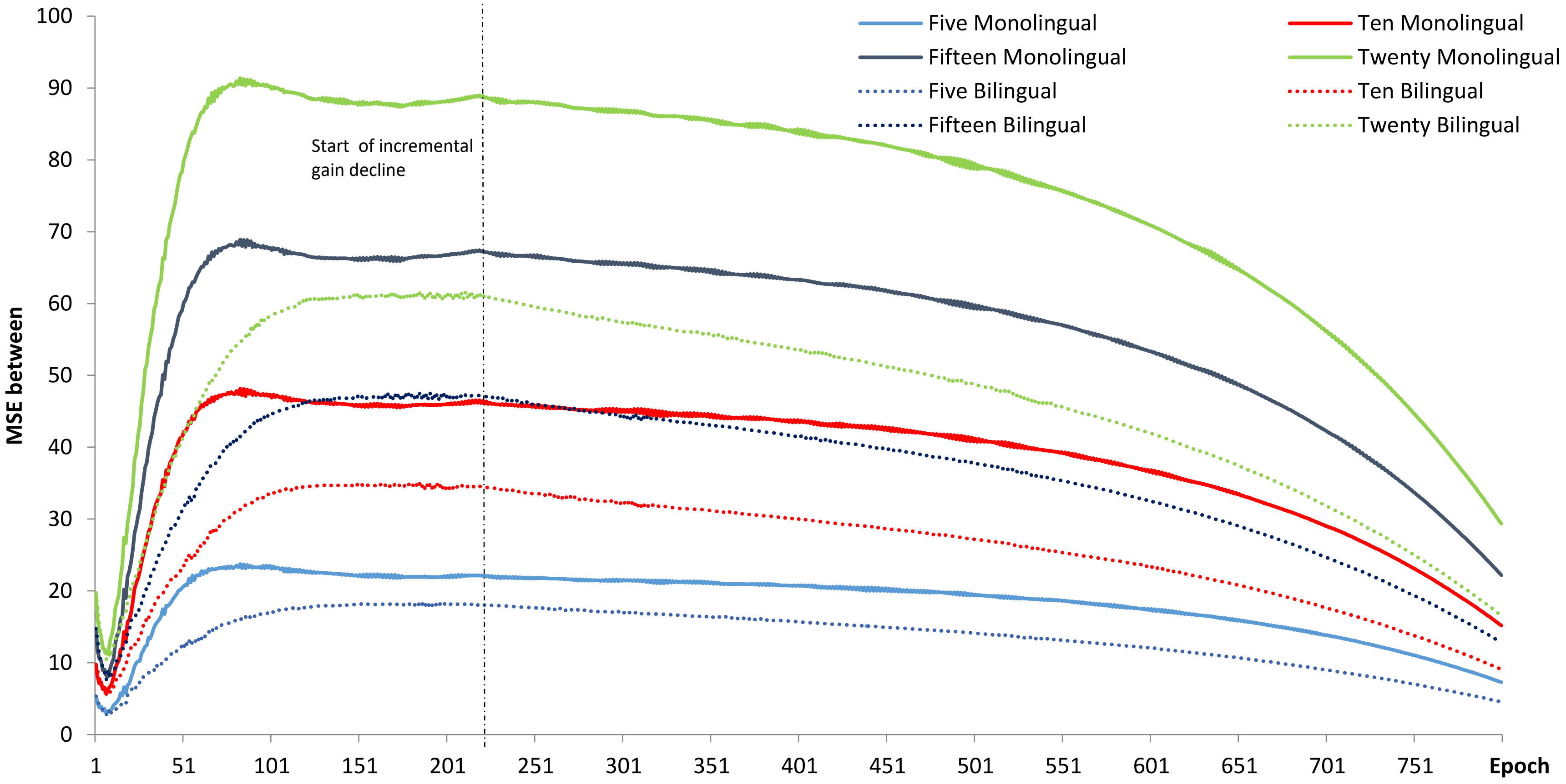


Figure 4.19: Projections of MSE values representing the between category representational spacing. Values plotted over lifespan of monolingual and bilingual networks for all hidden layer sizes.

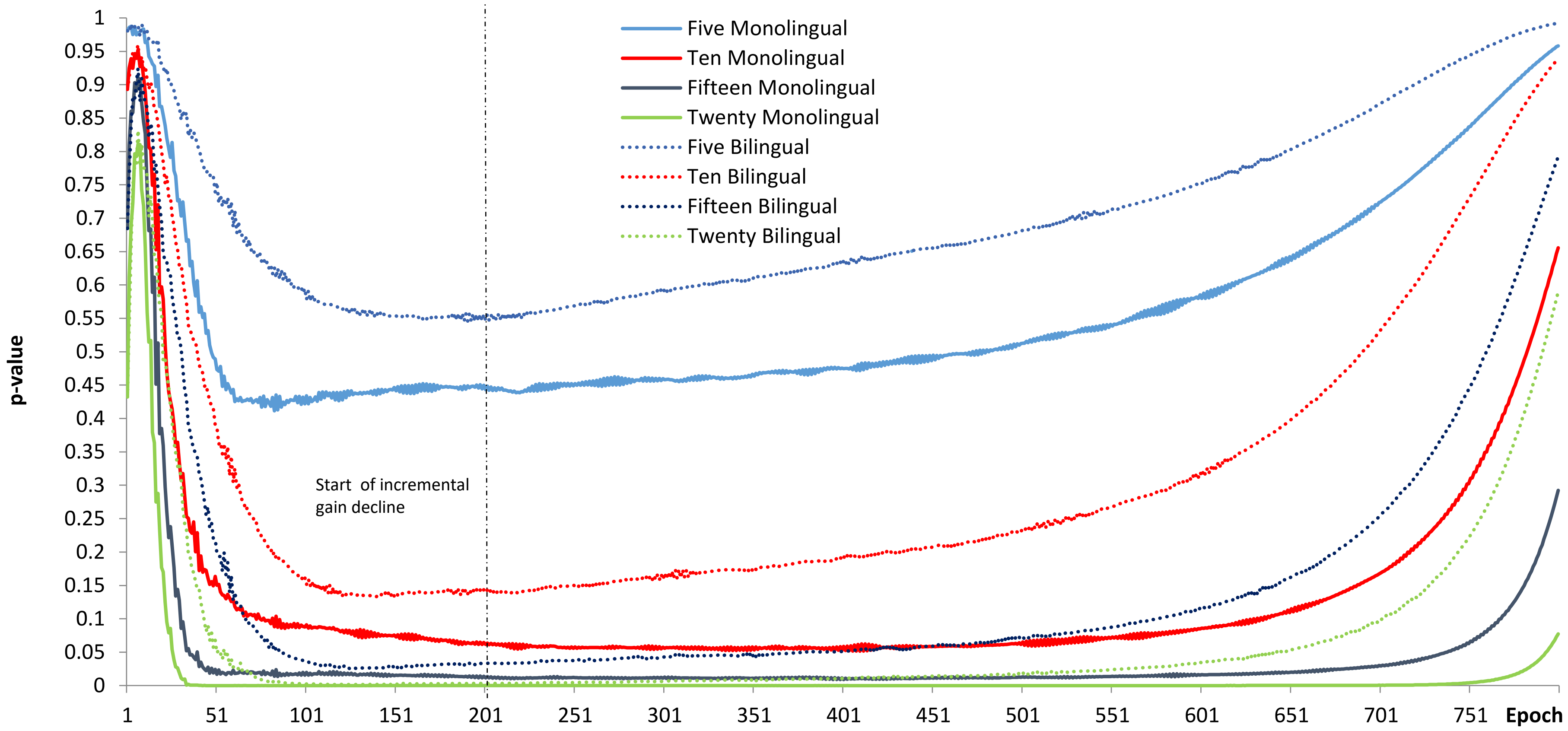


Figure 4.20: p-values representing significance of clustering (p<0.5 = significant increase in spacing, p>.95 = significant reduction in spacing (clustering)) of between category representations when compared to null distribution of the same. Values plotted over lifespan of monolingual and bilingual networks for all hidden layer sizes.

The plots demonstrate that overall, the monolingual models have greater separation than the bilingual models for both the within and between categories. This is due to the overall space requirement for the bilingual networks in that representations from two languages are fitted into the same representational space as one language for the monolingual models. However, the larger F-values seen for the bilingual networks (Figure 4.15) is due to the between category separation being larger than the within category separation for the bilingual models. The p-values representing the significance of the MSE within category representational spacing illustrate this by showing the longitudinal p-values entering significance over the training period for the bilingual network (Figure 4.18). However, the p-values for the monolingual models did not track into $p<.05$ at any point during training. The p-value plots representing the MSE between categories as a measure of spacing between representations in categories A and B shows that monolingual and bilingual networks are comparable (Figure 4.19). Therefore, the driver for the larger F-value for bilinguals was a significant clustering of representations within the categories.

Previous analysis of the model was able to look for differences between groups at a particular time point. However, in order to observe if the network type, whether monolingual or bilingual and the amount of layers were significant predictors of the division of semantic categories over time, a multilevel model was employed. Furthermore, this type of model accounted for the repeated measures, and therefore auto-correlative in nature, of F-values belonging to the same network. This was carried out by grouping them into network type and hidden layer sizes at higher levels.

Individual F-value scores were used as the dependent variable with the epoch as the first level predictor. The particular simulant used was assigned to level two with hidden layer size, the proxy of BRC, assigned as a random factor on level three. The null model was produced which did not contain any explanatory variables. This produced a log likelihood score of 94953.10.

Following this, a simple random intercept model was produced with whether the data point was from a monolingual or bilingual network included as a fixed explanatory variable (Mono/Bi):

$$\text{FValue}_{ijk} = \beta_{0jk} + \beta_1 \text{Mono/Bi}_k + e_{ijk}$$
$$\beta_{0jk} = \beta_0 + v_{0k} + u_{0jk}$$

In testing against a null hypothesis that $\beta_1 = 0$ the estimated slope was divided by its standard error. This produced a Z value. Therefore:

Z-score for $\beta_1 = \frac{(Est.Slope)\ -2.89}{(SE)\ 0.59} = -4.89$

Given a probability level of <.05 at a Z score of 1.96, the inclusion of network type into the model was significant ($p<.001$). Additionally, the model produced a log likelihood score of 94942.034. From this and the log likelihood score of the previous model a likelihood ratio test statistic (Λ) was calculated to compare how much more likely the data are under the new model than the null model:

$\Lambda = 94953.10 - 94942.03 = 11.07$ (1 d.f.)

One degree of freedom was used to due to one parameter difference between the models. When compared to the chi-squared distribution, the inclusion of multilingualism into the model was significant at $p<.001$.

The addition of time in the form of epochs was added as an explanatory variable. In order to add nonlinearity to the model, a quadratic term in the form of the epoch squared (Epochsq) was also introduced. Further, to confirm the lack of interaction observed with the ANOVAs at time points an interaction between BRC and whether the F-Value was from a monolingual or bilingual simulant was also added. However, this did not produce a significant improvement to the model:

$\Lambda = 90559.24$ (without interaction) – 90558.430 (with interaction) = 0.81 (1 d.f., n.s.)

Therefore the final model was as follows:

$$\text{FValue}_{ijk} = \beta_{0jk} + \beta_1 \text{Mono/Bi}_k + \beta_2 \text{Epoch}_{ijk} + \beta_3 \text{Epochsq}_{ijk} + e_{ijk}$$
$$\beta_{0jk} = \beta_0 + v_{0k} + u_{0jk}$$

Where $\beta_1=-2.89$, $p<.001$; $\beta_2=0.041$, $p<.001$; $\beta_3=-0.001$, $p<.001$

A log likelihood ratio test statistic was calculated between this model and the null model:

$\Lambda = 90558.43 - 94953.10 = 4394.67$ (4 d.f., $p<.001$)

Using the chi squared distribution with four degrees of freedom, representing the total amount of parameter differences between the models, the likelihood ratio test statistic was significant (p<.001).

4.7.3 Inhibition within the networks

To test if the deliberately implemented feature difference (language tags) created more inhibition in a bilingual network than a monolingual network, the weights from the language tags to the hidden layers of the twenty hidden layer version of both network types were explored. Initially, a scatterplot was produced which illustrated the weight values from language tags of input set to the hidden layer of the twenty node versions of both the monolingual and bilingual networks (Figure 4.21). What was observed from the scatterplots was a negative relationship between the tags representing L1 and L2 with regards to the weighting of the connections between them and the hidden layer. This means that the language tags are contributing factors in biasing the hidden layer towards one language or the other by inhibiting whichever language is not active. If the weights are positive for one language, they are negative for the other. The lack of relationship demonstrated by the monolingual network shows indicates the lack of necessity for differentiation in a single language environment.

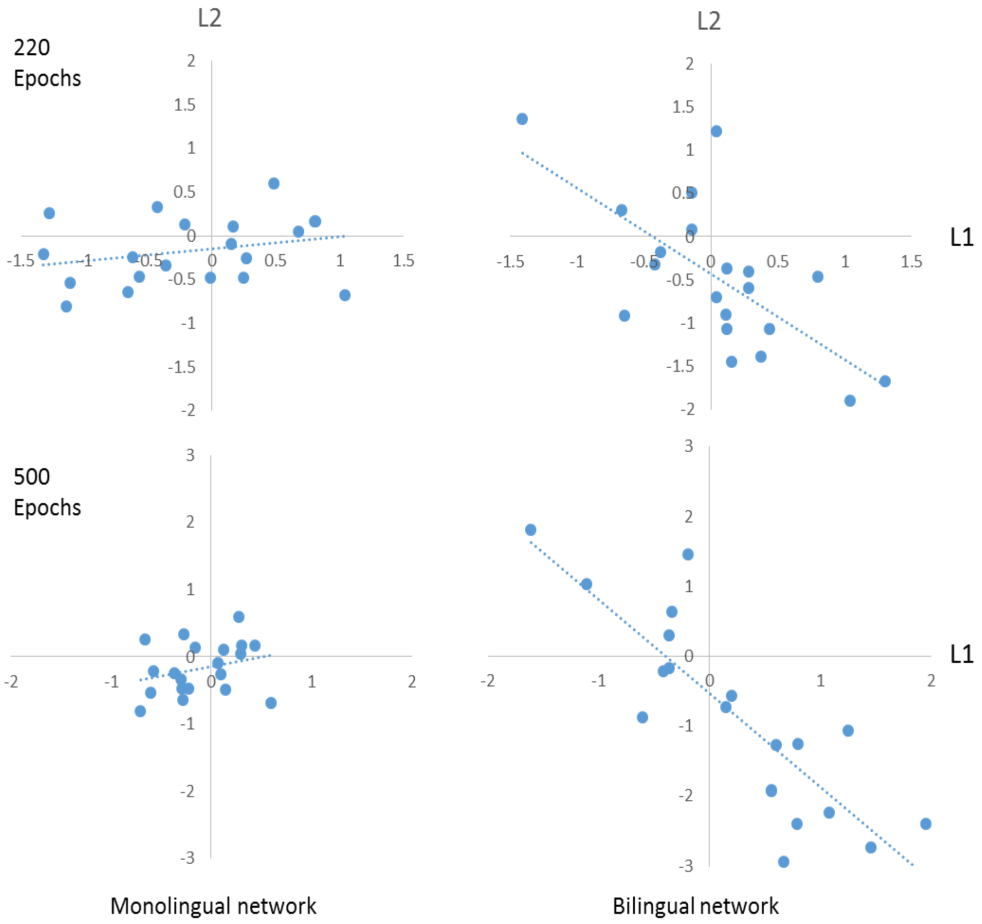


Figure 4.21: Example scatterplots of weights from language tags to the 20 node hidden layer of monolingual and bilingual networks at 220 and 500 epochs.

In order to provide a quantitative measure of the negative relationship between language tags, a correlation coefficient was calculated at several points over the lifespan of the networks (Table 4.3).

Table 4.3: Pearson's correlation coefficients representing inhibitory action between active and inactive language tags of monolingual and bilingual networks. * Significant at $p<.05$, ** Significant at $p<.001$.

	Epochs							
Network	100	220	300	400	500	600	700	800
Monolingual	.24	.28	.27	.28	.28	.29	.29	.34
Bilingual	-.56*	-.69**	-.75**	-.80**	-.84**	-.87**	-.90**	-.90**

The correlation coefficient calculated at points throughout the training of the network indicates an increase in opposition of weights and therefore an increase in inhibition over the lifespan of the network for the bilingual network. Therefore, it appeared that ageing increased the amount of control in bilinguals. Whilst some increase was observed in monolinguals, at no point did the relationship become significant. The correlation co-efficients for all hidden layer sizes were investigated for the bilingual network (Table 4.4).

Table 4.4: Pearson's correlation coefficients representing inhibitory action between active and inactive language tags of bilingual network over all four hidden layer sizes. * Significant at p<.05, ** Significant at p<.01, *** Significant at p<.001.

	Epochs							
Hidden Layer size	100	220	300	400	500	600	700	800
Five	.13	-.81	-.70	$-.91^{*}$	$-.98^{*}$	$-.98^{**}$	$-.92^{*}$	$-.99^{**}$
Ten	$-.79^{*}$	$-.70^{*}$	-.63	$-.85^{**}$	$-.80^{**}$	$-.82^{**}$	$-.97^{***}$	$-.83^{**}$
Fifteen	$-.83^{***}$	$-.80^{***}$	$-.73^{**}$	$-.83^{***}$	$-.88^{***}$	$-.96^{***}$	$-.92^{***}$	$-.94^{***}$
Twenty	$-.56^{**}$	$-.69^{***}$	$-.75^{***}$	$-.80^{***}$	$-.84^{***}$	$-.87^{***}$	$-.90^{***}$	$-.90^{***}$

Comparing the strength of relationships between the weights from each language tag demonstrated an increasing prevalence of highly significant negative relationships as the hidden layer size increased. However, as a sample exercise, comparing the correlations from samples at five and twenty hidden layer size at 500 epochs (-.98, n=5 & -.84, n=20 respectively) Fishers r –to-z transformation (Steiger, 1980) showed that the difference was not significant (z = 1.44, p = .08).

4.8 Discussion

The second simulation in this chapter represents an exploration of the way in which bilingualism influences how language representations are stored and developed. This study explored differences in representational spacing in a single language between monolingual and bilingual models of semantic representations. This was simulated through the association of randomly-generated input with their lexical counterparts in one or two languages. As with the previous simulation, both models were trained over a number of epochs with different levels of BR represented by different in layer sizes. However, further difference to the previous simulation was implemented with the introduction of a gain change in the log-sigmoidal transfer function to represent ageing (Bäckman et al., 2010; Servan-Schreiber et al., 1990).

The first main finding of this simulation mirrors that of the first simulation in that the spacing of representations within a single language of both monolingual and bilingual models differed in that representations in the bilingual networks were significantly more clustered than in the monolingual models. However, this time the model was simulating semantic rather than lexical simulations by associating ‘pictures’ with their meaning in one or both languages. Furthermore, when the categories within L1 of both languages were explored, differences were also found in representational spacing. Both of these findings might be characterised by the simple explanation that spacing between representations for the bilingual language is reduced because of the need to fit more representations into the same representational space as the monolingual model. However, when the within and between categories representational spacing were explored, it was evident that the ratio between these two factors differed between monolingual and bilingual models.

The expectation may have been that if representations were generally more spaced out in the monolingual model then the distance between semantic categories may have also reflected this. However, the distance between representations between categories A and B were comparable. Therefore, the larger F-values observed for the bilingual models were due to the significant clustering of representations within the semantic categories of the bilingual model.

During the changes in the representational spacing over age, the performance of the network did not change. This differs to a previous neural network model of cognitive reserve in which one of the simulations also represented ageing by changes to the transfer function (Thomas, 2008). The performance in that simulation showed some decline which recovered at varying rates according to reserve size and task type. The current simulation provided a more valid application of the change to the transfer function since it was incremental rather than at three specific time points in the network age for the study by Thomas (2008). The network in the current study mitigated any significant decline in performance by adjusting for the error at each epoch. Rather than a decline in performance, the ageing implementation in the current study manifested itself as a changes in the representation spacing.

Given the similarity in the between category separation of semantic representations between monolingual and bilingual models, similar performances between monolinguals and bilinguals can be predicted in tasks requiring switching from one category to the next. Verbal tasks typically require the individual to retrieve a number of words from a given categories and it is within these tasks that a bilingual disadvantage is normally found (e.g. Gollan et al., 2002). However, retrieval across categories may present a different picture and even a bilingual advantage due to greater executive control when switching between categories. Such a study would demonstrate that the bilingual advantage or disadvantage might be a function of the task structure in terms of whether good performance in the task requires greater separation of to be retrieved exemplars.

In addition to the suggestion that greater overlap between representational spacing within the categories of language for bilingual models could be a source of great inhibition in bilinguals due to the increased recruitment of inhibitory processes, analysis of the weights from the language tag to the hidden layer of the model showed an increasingly negative relationship between weights from language tags representing L1 and L2. This developing bias upon the hidden layer to represent one language rather than the other existed in the bilingual network due to the influence of the tags.

The influence exerted upon the hidden layer of the bilingual model by the tags representing each language was due to the contribution the tags made to separating the two languages given that the rest of the input features of the ‘pictures’ were identical. Given that storage of semantic information in both languages occurs for the same picture, the real-world application of the language tags in this simulation was that of context. Therefore, delineation of semantic information into language specific stores could be provided by the environment only. This might appeal to theories of a single conceptual store for bilinguals with context providing enough information for appropriate recollection.

The effect of BR represented by hidden layer size was also investigated when looking at the correlations between the two different activations of the language tags.

The significance of the negative relationships between both L1 and L2 activations appeared to increase over the size of the hidden layer. However, initial inferential testing between two samples did not demonstrate a clear difference between the low and high extremes of hidden layer size. Therefore, more research should be carried out to investigate whether BR also has an effect on the inhibition within the network.

The significant main effect of hidden layer size, as a proxy of BR and its interaction with whether or not the network was monolingual or bilingual demonstrates the importance of this passive factor in cognitive reserve. An increase in brain substrate led to the facilitation of greater spacing out of the representations. This was true of Euclidean distances, plots of the first three dimensions resulting from multidimensional scaling, and the F-value calculated to demonstrate separation of categories. In terms of distances between semantic categories, higher BR individuals demonstrated a non-significant distribution of representations. With increased clustering leading to greater recruitment of inhibitory processes over age, according to retrieval induced inhibition, it might be predicted that monolinguals with the highest measures of BR may manifest lower measures of CR in old age. This would set up BR and CR as two different protective measures and contribute to the idea that BR is not simply CR on another level of description.

Regardless of differences in representational spacing over the lifespan, longitudinal analysis revealed that as ageing progressed, representations within all hidden layer sizes of both monolingual and bilingual networks converge. This was partly due to utilisation of the gain reduction over lifespan as a proxy of incremental dopamine reduction over age (Bäckman et al., 2010). Simulations made in the absence of this manipulation demonstrated a continual spacing of representations over the entire duration of the lifespan of the networks (not shown). Convergence to the point at which representations are no longer distinguishable from each other may be considered a collapse in cognitive functioning. This therefore supports the threshold model of resilience to cognitive ageing (Stern, 2002; Figure 4.1) in which differing levels of cognitive reserve are manifest by differences in the time at which decline becomes apparent. However, like the simulation in this chapter, convergence occurs near the end of the lifespan. Further increases to the validity of the model can be made with adjustments made to the rate at which dopamine decline occurs.

With the majority of the input controlled for and the difference between the input ‘pictures’ due to the activation of language exclusive context tags, further research into the ability of the model to separate representations in L1 and L2 could be explored by varying the differences in context between both languages. Such investigation may lead to the underlying causes of the variation in the bilingual advantage that arises due to studies involving bilinguals who speak languages with greater differences between features. A prediction in this case would be that the greater the difference between the two languages, the lesser the amount of inhibition that is required to separate the two languages. Therefore, the bilingual advantage for these individuals would be smaller than those for whom the features of both languages are very similar.

Both simulations in this chapter demonstrate a greater clustering of representations within the bilingual models when compared to the monolingual models. Reduce spacing between lexical representations in a bilingual network was observed in the first simulation. Furthermore, significant clustering of semantic representations within the categories of the bilingual network when compared to a random distribution for all hidden layer sizes was observed for the majority of the lifespan of the models. This can be interpreted in terms of the retrieval induced inhibition hypothesis (Anderson et al., 1994). The bilingual advantage and the buildup of cognitive reserve occurs due to repeated and greater recruitment of inhibitory mechanisms at the level of semantic and/or conceptual items in a bilingual individual due to close spacing and overlap between representations and categories within a language. This interpretation contributes to the literature regarding the bilingual advantage which may provide the genesis for cognitive reserve in ageing individuals (Bialystok et al., 2007).

Increased spacing of representations as a proxy of inhibition has been demonstrated over the lifespan of the network. Furthermore, inhibition within the network itself from competing language tags has been demonstrated to increase over the lifespan of the model. Therefore, the current simulation supports studies which demonstrate a greater bilingual advantage for older adults (Bialystok et al., 2004).

4.9 Conclusion

The two simulations within this chapter represent a series of novel analyses of the representational space in simple three layer networks portraying monolingual and bilingual speakers under the circumstances of learning a particular language and learning semantic information. The results of the first simulation demonstrated that lexical representations in a mature monolingual network were more distributed than those representations in a bilingual network. The second part of this chapter investigated the development of semantic representations of words within a single language stored either in a bilingual speaker or monolingual speaker. The results of this study demonstrated greatest spacing between representations in total L1 in the monolingual network. Conversely, greater clustering of categories within L1 was observed in the bilingual network. This means an increasing overlap between representations at both the level of the single representation and within the categories which they represent. According to the retrieval induced inhibition (Anderson et al., 1994), such a relative reduction in spacing would increase the need for greater recruitment of inhibitory processes during recall. Therefore prolonged practice of speech in both languages would lead to increased cognitive reserve in bilinguals.

Chapter Five: The relationship between language, cognitive reserve and executive control

5.1 Introduction

The relationship between bilingualism and Cognitive Reserve (CR) appears robust (Abutalebi, Guidi, et al., 2015; Guzmán-Vélez & Tranel, 2015; Olsen et al., 2015). The bilingual advantage (e.g. Bialystok, 2006; Costa, Hernández, & Sebastián-Gallés, 2008) suggests that bilinguals perform better at tasks requiring executive processing. This then provides a clue as to the possible contribution of bilingualism to CR, specifically neural reserve. This chapter explores the relationship between environmental proxies of CR and executive processing and executive control with a focus on the more recently described proxy of bilingualism (Craik et al., 2010). This is especially important since more recently, there has been an upsurge in the literature suggesting the bilingual advantage is the result of a publication bias with confounds such as education providing the real effect (de Bruin, Treccani, & Della Sala, 2015; Paap, Johnson, & Sawi, 2015). Therefore the main purpose of this chapter is to explore the bilingual advantage and discuss how it relates to CR. Further, in order to investigate the cognitive beginnings of the more traditional proxies of CR, relationships between measures of these and executive control processes will also be explored. Two large studies investigating two aspects of executive processing are included in this chapter, both of which combine questionnaire and behavioural investigation.

5.1.1 Bilingual advantage and task switching

In general, the bilingual advantage is thought to be the result of the continued effort of keeping multiple languages apart when speaking the appropriate one (Hernández, Martin, Barceló, & Costa, 2013). Most studies have focused on the executive processes of suppressing conflicting responses and the bilingual advantage in the context of inhibition has been discussed in chapter four. However, whilst executive control processes are complex and interactive, some attempt has been made at separating them out (Miyake et al., 2000). As such, task switching is one domain of executive control in which a limited amount of research has demonstrated that multilinguals perform better than monolinguals. In general terms, task switching relates to the latency involved in switching from carrying out one task to another. This is generally compared to the latency of carrying out a second consecutive trial of the same task. The resulting subtraction of reaction times associated with repeating the task from those associated with changing the task results in a switch cost. Early iterations of a paradigm known as the embedded figures task provides a clue as to the difference in ability between monolinguals and bilinguals to switch tasks, even at an early age. Known in its physical incarnation as the dimensional change card sort task, also described in the Chapter four, bilingual and monolingual children between the ages of four and five years were asked to sort images that varied on the dimensions of shape and colour (Bialystok, 1999; Bialystok & Martin, 2004). Specifically, they were required to put the cards into boxes according to a rule based on one-dimension, for example, colour. Therefore, the participant would be required to put blue cards in one box and red cards in another. Later in the task, the participant would be required to switch to a different rule and sort the cards according to another dimension such as the shape. For example, this might mean putting circles in one box and squares in another. Both sets of children performed equally in the initial trials prior to the second rule being provided. However, the results from both studies demonstrated a significant advantage for bilinguals when the target dimensions were perceptual features of the stimulus. The subsequent divergent performance between the two groups was proposed to be the result of the differential ability to switch between rules and inhibit the rule that was not relevant at the time.

The difference between monolinguals and bilinguals in the ability to switch tasks appears to endure into adulthood with more complex methods of measuring the specific aspects involved in task switching. For example, monolingual (mean age = 18.7 years, SD = .9) and bilingual students (mean age = 19.5 years, SD = 1.5) engaged in a task switching paradigm (Prior & MacWhinney, 2010). In this experiment, the participant was required to sort consecutively presented red or green circles and triangles according to a cue which required the participant to sort them either by shape or colour. No main effect was found between language groups on reaction times. However, an interaction between language groups and trial type was found. This was driven by a much reduced switch-cost for the bilingual group. Whilst an advantage for inhibitory-based paradigms can be related to a resistance to distracter interference, findings in this particular domain of executive control demonstrate an advantage for the shifting of mental sets.

The need to switch from one language to another is common in communities in which two languages are widely spoken and understood as well as more common situations in which bilinguals will switch back to their ‘mother tongue’ in order to better communicate a particular concept. For example, both task switching and the neural correlates of the executive processes were investigated in a study involving 21 Spanish monolinguals and 19 early bilinguals who spoke both Spanish and Catalan (Garbin et al., 2010). The bilingual group in the circumstances switch between languages frequently in social situations and therefore task switching as an executive control process would be well practised. The tasks in this experiment consisted of sorting red and blue circles and squares into either shape or colour. The results demonstrated a larger switch cost for monolinguals than the bilinguals. Furthermore, there was no significant difference between reaction times for switch and non-switch trials for bilinguals. The relative ease of moving to another task is in accordance with the idea that this would be more practised in bilinguals than monolinguals. Furthermore, this study was undertaken under fMRI imaging conditions and as such, the researchers were able to ascertain that different cortical networks were engaged for monolinguals and bilinguals when switching task. Monolinguals demonstrated larger BOLD signal is for the left inferior frontal lobe as well as the anterior cingulate cortex (ACC) suggesting a larger effort involved in inhibitory processing for monolingual than bilinguals in the contribution towards task switching. The strong support for a bilingual advantage in this population also suggests that the frequency of switching between languages may also be a factor.

5.1.2 Variability of the bilingual effect

Task switching performance is not simply related to bilingualism but also the frequency in which individuals have to make switch between languages themselves. This obviously depends on circumstances and in the example of the Spanish - Catalan bilinguals in the study by Garbin et al. (2010), language switching within the same context or dual-language context (DLC) was a natural circumstance of the region in which they lived. This idea is explored in terms of DLC bilinguals and those who rarely need to switch languages, known as single-language context (SLC) individuals (Hartanto & Yang, 2016). One hundred and thirty three bilinguals reported the extent to which they used to languages in the same and different context. Given a mean split of the scores relating to these responses, the participants were divided into 75 DLC and 58 SLC. Both groups were required to take part in a typical colour and shape sorting task as described above, this time using green and red triangles and circles. The results found that whilst DLC and SLC individuals did not differ on background measures such as non-verbal intelligence and general vocabulary, they differed in switch costs with a smaller switch cost for DLC bilinguals. Furthermore, DLC individuals were significantly faster than SLC individuals in switch trials but not repeat trials. This final finding reflects comparisons made between groups of bilinguals and monolinguals suggesting that switch cost is not the preserve of bilinguals per se but is something that results from the practice of switching between languages.

As well as the frequency of switching between languages, the combination of languages held as well as the level of proficiency in the Heritage Language (HL) might also be an issue in both task switching and inhibition. Tao, Taft, and Gollan (2015) investigated groups of Spanish-English bilinguals as well as Mandarin-English bilinguals. Measures were taken of HL as well as an English verbal fluency task and for the main experiment, participants were required to carry out the Colour-Word Interference Test (CWIT). The CWIT had four conditions each of which consisted of 50 items printed on a single page. Each of the conditions related to either word reading of colour words in black ink, colour naming of coloured patches, and an interference (Stroop incongruent) condition in which participants had to state the colour of a colour name presented in an incongruent colour. The final condition related to task switching in which participants were required to switch between the Stroop and word reading conditions. A measure of task switching was gained by taking the reaction times of the switching condition and subtracting inhibition scores. The results demonstrated a smaller switch cost for both groups of bilinguals compared to monolinguals. However, the effect for switch cost for Mandarin-English bilinguals was smaller than Spanish-English bilinguals but still significant. Neither group of bilinguals demonstrated an advantage for inhibition cost compared to monolinguals. This study encompasses the overall variability in findings in studies investigating the bilingual advantage with group specific advantages in task switching and challenging results for the bilingual advantage in inhibitory cognitive processes.

Differences in the type of switch cost have also been found between bilinguals and monolinguals. Classic switch-cost, which is the result of subtraction of reaction times when one task is followed by a different task from the reaction time provided by the repetition of the same task, was investigated by Wiseheart, Viswanathan, & Bialystok (2016). Furthermore, they examined a Global Switching Cost in which the difference between mean reaction times from blocks of repeat trials and switch trials compared. This latter measure was a reflection of the ability to reconfigure Stimulus-Response (S-R) associations. Using a task switching paradigm using pictures as non-verbal cues for sorting blue and red horses and cows, the researchers demonstrated a global switching cost. This demonstrates an improved ability of bilinguals compared to monolinguals to reconfigure S-R associations. However, unlike previous studies (Garbin et al., 2010; Prior & MacWhinney, 2010) no difference in classic or local switching cost was found between monolinguals and bilinguals, a factor which should also reflect an ability to reconfigure S-R associations. These studies demonstrate the variability already present within the bilingual advantage. The next section describes research which refutes the idea altogether.

5.1.3 The bilingual advantage under fire

Recently, the reported subtleties now evident in the relationship between task switching and multilingualism have also been joined with a number of studies which have demonstrated no relationship between executive control processes as a whole and multilingualism. For example, in another sample of Spanish monolinguals and Spanish-Catalan bilinguals participants were required to take part in three experiments, all of which represented implementations of task switching relating to the change in stimulus- response (S-R) required when moving from one task to the next which has the same stimulus but different task requirements (Hernández et al., 2013). In the first experiment, the authors explored the effect of bilingualism on the ability to reconfigure S-R mappings as well as the reactivation of S-R. The experiment required participants to match one choice card with four key cards according to one of two different rules. Switch cost was calculated as normal and measured as an ability to reconfigure the S-R mapping. Further, the use of implicit and explicit cues allowed the researchers to measure restart S-R mapping by exploring the difference in reaction times between the first trial after an explicit repeat cue and the subsequent repeated trial. In the second experiment, participants had to respond to stimuli according to a shaped cue. Some stimuli were paired with a single cue (univalent) whereas other stimuli were paired with multiple cues which meant that the participant had to respond to the same stimuli differently (bivalent). Furthermore, a semi bivalent condition was used in which the same key was pressed but a different amount of times according to the stimuli, meaning the mapping was not reversed but changed. By using these trials, the authors were able to investigate task switching only when switching tasks into a trial type that conflicts with the previous one. The final experiment was a replication of the task switching paradigms used in a number of studies demonstrating the difference between monolinguals and bilinguals in this executive control process (Prior & MacWhinney, 2010). The stimulus included two shapes with two cues presented prior to the stimulus as described above. The results from the first two experiments suggested that bilinguals were better at restarting their S-R mappings given an explicit cue within a series of implicit cues in the first experiment and overall faster reaction times in the second experiment. However, no reduction in switch cost was found in any of the experiments. This study tested number of different experimental aspects and paradigms which demonstrates an elusiveness of the effect of bilingualism and executive control.

In addition to findings supporting a lack of advantage for task switching, some studies investigating inhibitory control and bilingualism have failed to show a difference between monolinguals and bilinguals. For example, no difference in the amount of Stroop interference was found in a sample of older and younger monolinguals and bilinguals (Kousaie & Phillips, 2012). A total of 118 participants carried out a variation of the classic Stroop task. Comparisons were made between both older and younger participants and monolinguals and bilinguals. The results demonstrated that although there was a general speed advantage for younger bilinguals, no difference between monolinguals and bilinguals in terms of smaller Stroop interference was apparent. Further, a large sample of 252 monolingual and 252 children from primary school third-grade to high school second-grade was tested for performance differences in both verbal and non-verbal versions of the Stroop task (Duñabeitia et al., 2014). As per the classic Stroop task, the first experiment required participants to name the colour of four different colour words. The second, non-verbal version of the Stroop task, used number pairs in which congruency related to the relative size of the digits. Therefore, the larger of the two digits would be in the larger font size. In both experiments, the Stroop effect was apparent and overall latency decreased with age. However, comparison between monolinguals and bilinguals over all age stratifications of interference effects did not yield any significant differences between them.

Such null findings may be more common than initially thought, as there may be a publication bias towards studies demonstrating a difference between monolinguals and bilinguals in executive processing in general (Paap & Greenberg, 2013). In an investigation of this suggestion, de Bruin, Treccani, & Della Sala (2015) looked at conference presentations as an example of a truer picture of studies investigating the relationship between executive control and bilingualism. From a search of 169 conferences that were organised between 1999 and 2012 they identified 128 abstracts that were presented over 52 different conferences. The abstracts were classified into four different categories. The first category contained data that supported a bilingual advantage, the second category represented studies which showed some data which was compatible with a bilingual advantage. The third and fourth categories reflected some refutation of the bilingual advantage with the third category representing studies which partly challenge the idea and fourth category represented studies that fully challenged the bilingual advantage. When looking at those studies which had been subsequently published, the authors found an effect of the type of results gained from the study and their publication. 68% of studies which demonstrated support for the bilingual advantage were published and only 29% of those studies which challenged the bilingual advantage being published. Such a potential bias requires some explanation but may also contribute to a suggestion that it is not repetitive execution of control processes which contributes to cognitive reserve. In direct response to de Bruin et al. (2015), Bialystok, Kroll, Green, MacWhinney, & Craik (2015) state that the problem with the claims of publication bias is that they were based on conference submissions and there was no way of knowing the amount of these which were eventually submitted for publication. Further, they question the methodology of the meta-analysis in combining null and negative effects into a single category. In not differentiating between the two, the authors state that de Bruin et al. (2015) failed to provide a fair reflection of publication bias since a true falsification of the bilingual advantage would require as many negative effects as there were positive. In categorising null and negative effects together, de Bruin et al. failed to make this distinction.

5.1.4 The bilingual advantage is not inhibition based

One explanation for such mixed findings is the incorrect pigeonholing of executive processing into a number of different putative processes. This would still preserve the proposition that neural reserve derived through bilingualism is the result of exective control process, however ill-defined they are. Any differences between monolinguals and bilinguals in the Stroop task (Bialystok, Craik, & Luk, 2008b) are perhaps not due to performance differences in the ability to inhibit information due to the assertion that the Stroop task is a measure of the ability to inhibit a prepotent response. Instead, differences between monolinguals and bilinguals in Stroop task performance may be due to some other facet of executive processing not yet ascribed a particular component. As such, these differences are not captured by standard ‘inhibitory’ tasks and require new paradigms to investigate properly the aspects of executive processing that actually differ between monolinguals and bilinguals.

A review of the evidence suggesting that the bilingual advantage is mediated by inhibitory control also suggests that any advantage may not necessarily be the result of non-linguistic inhibitory control processes (Hilchey & Klein, 2011). The authors reviewed the findings from a number of studies which used several inhibitory paradigms such as the Simon task, the Flanker task, and the spatial Stroop. Whilst the authors found a performance increase for bilinguals over monolinguals, this was generally true for both congruent and incongruent trials. Therefore, the authors concluded that it is unlikely that the advantage that bilinguals have over monolinguals is due to improvements in inhibitory control but rather a general processing advantage that is persistent throughout life span.

The variability in the results related to task switching and different populations demonstrates that the same might be said for task switching. Rather than a particular neural mechanism explicitly committed to reconfiguring S-R. There may be some other executive control process which contributes to some aspects of task switching but maintains a more global functionality. Subtleties in the results of task switching paradigms demonstrate that those cognitive mechanisms that underlie task switching per se may not be explicitly exercised (Bialystok et al., 2015). Conversely, there may also be an interaction with the type of bilingual, be it the languages used by the bilingual (Tao et al., 2015) or the frequency of switching between them (Garbin et al., 2010; Hartanto & Yang, 2016). What is important to point out is that these studies do not refute the evidence put forward in regards to bilingualism and cognitive reserve. Rather they may indicate that the source of cognitive reserve is not as easily explained as the reinforcement of one of the currently established components of executive processing. What is required is evidence of a direct link between bilingualism and cognitive reserve.

5.1.5 Biology as the direct link between bilingualism and cognitive reserve

If the bilingual advantage is a red herring then the connection between bilingualism and CR needs further explanation. A more direct clue as to the link between the bilingual advantage and CR can be found in studies investigating the biological basis of bilingualism. Brain networks which are strengthened by bilingualism would also provide a tangible buffer against age-related decline. An early Diffusion Tensor Imaging (DTI) investigation of biological correlates of multilingualism suggested differences in DTI and resting state connectivity (Luk et al., 2011). Increased connectivity was observed between the inferior frontal region and a number of posterior structures in the parietal, temporal and occipital cortices. More recently, studies of resting state connectivity have indicated stronger connectivity in bilinguals than monolingual in the Frontoparietal Control Network (FPC) network (Grady, Luk, Craik, & Bialystok, 2015). This network includes frontal structures such as the dorsolateral prefrontal cortex (DLPFC) and the ventrolateral prefrontal cortex (VLPFC) and is thought to act as a higher-level control network of Executive Control (EC) processes in general and their application in accordance with task demand.

Imaging studies carried out in parallel with EC tasks have also uncovered differences in the strength of frontal cortex activation between monolinguals and bilinguals

(Gold, 2014). In two experiments (Gold, Kim, Johnson, Kryscio, & Smith, 2013), designed to compare the performance of bilinguals and monolinguals in task switching performance, older and younger monolingual is and bilinguals carried out a perceptual switching task, a computerised version of the dimensional card sorting task (Bialystok & Martin, 2004). The results from the first experiment demonstrated that for older adults, but not younger adults, there was a bilingual advantage in task switching performance. In the second of the two experiments, participants were scanned whilst undertaking the task. The behavioural results were the same as the first experiment. Such results are consistent with that the finding in Chapter four of increasing inhibition over age for bilingual networks. Furthermore a decreased BOLD signal, similar to the younger monolingual and bilinguals, was observed in combination with higher task switching performance in the older bilingual compared to older monolingual adults. This biological evidence suggests a direct relationship with cognitive reserve given the attenuation of the BOLD signal as a reduction in the need for over-recruitment.

Differences in the macro structure of the parietal cortices may also endure into old age and confer some benefit with regards to offsetting age-related decline. For example, Grey Matter Volume (GMV) was compared between English speaking monolinguals and English-Spanish speaking bilinguals (Olulade et al., 2015). This was carried out in the absence of an executive control task to control for any specific measures of executive control in order to provide a biological indication of experiential changes. The authors found greater GMV in the parietal cortex as well as the VLPFC. These regions are directly related to an executive control network (Grady et al., 2015). With regards to the combination of languages used by bilinguals, greater GMV was found in Cantonese-mandarin bilinguals compared to

Cantonese-English bilinguals (Abutalebi, Canini, Della Rosa, Green, & Weekes, 2015). This final result suggests that greater similarity of languages means that greater inhibitory processes need to be recruited to suppress highly competing linguistic codes. Regarding task switching, GMV differences were also found between monolinguals and bilinguals in the DorsoLateral PreFrontal Cortex (DLPFC), a region in which activation has been observed during language switching in bilinguals (Abutalebi & Green, 2007).

5.1.6 Aims

The research in this chapter aims to clarify the relationship between bilingualism and executive control. Approximately 80% of studies carried out since 2011 have demonstrated no support for the bilingual advantage (Paap et al., 2015). However, support for the contribution of bilingualism to cognitive reserve remains robust (Abutalebi, Guidi, et al., 2015; Guzmán-Vélez & Tranel, 2015; Olsen et al., 2015). Furthermore, the biological evidence suggests clear differences between monolinguals and bilinguals. Therefore, it may be that cognitive reserve conferred by bilingualism is a result of different mechanisms to those that produce a bilingual advantage. It may also be the case that cognitive reserve by other means such as use of education, lifestyle etc. may not be the result of the same mechanisms. Therefore, the studies in this chapter attempt to investigate the relationship between new and old proxies for CR and their relationship with tasks requiring executive control. This was achieved by taking measures of CR via traditional proxies, such as years of education using the CRIQ questionnaire as well as measures of bilingual language use using a bilingual questionnaire. It is important to note that measures of language use are not included in the CRIQ. If a relationship between scores on the CRIQ and language use and the CRIQ were to be found this would support the suggestion that bilingualism is simply a proxy for educational attainment (Alladi et al., 2013), measures of which are included in the CRIQ. Two behavioural tasks are used in this study to measure different aspects of executive control, the Stroop task and a version of the dimensional task switching task.

5.1.6.1 Cognitive reserve in younger adults

In order to reasonably measure the relationship between CR and behavioural performance in younger adults, the existence of CR beyond age-related decline and pathology to younger adults needs to be assured. Imaging support for the existence of neural compensation in younger adults has been demonstrated via imaging studies (Reuter-Lorenz & Cappell, 2008). However, the study in Chapter three suggests that the behavioural evidence for compensation in younger adults is mixed. Neural reserve, the aspect of CR with which bilingualism might be associated, is the strengthening neural pathways normally associated with a task (Stern, 2003). Therefore, its manifestation in younger adults may be different.

The biological evidence related to environmental proxies for cognitive reserve including those described in relation to a language above suggests that cognitive reserve is something that is built up over the lifespan. Studies such as the one carried out by Gold (2014) suggest that one of the ways that neural reserve could be demonstrated in younger adults is the relative reduction in activation demonstrated when carrying out tasks. This suggests that cognitive reserve manifests itself in a reduced need for processing effort in younger individuals. The ability to provide a level of functioning with lower amounts of substrate may reflect the strengthening of the neural substrate associated with that cognitive function (Holtmaat & Svoboda, 2009).

Imaging studies demonstrating the relationship between lower levels of activation in carrying out tasks and measures of cognitive reserve have contributed to a triad consisting of environmental factors over the lifespan, reduced processing and the offset of cognitive decline in older adulthood. For example, in a fMRI study old and young participants were rated on their level of cognitive reserve using to measures of IQ as a proxy measure (Stern et al., 2008). Participants were then given two tasks with differing cognitive demands. These were delayed letter and shape Sternberg tasks. In each of the two tasks, difficulty was manipulated over three levels. Imaging was carried out to attempt to identify a cognitive reserve specific brain network common to both tasks as well as task demand. In the younger adults, increased cognitive reserve was associated with increased expression in the right and left superior frontal gyrus together with reduced expression in the left medial frontal gyrus. Further, the use of proxies to measure CR in studies which have included younger adults in their sample have also demonstrated that this category have successfully shown less task related activation in association with higher levels of CR (Habeck et al., 2003, 2005; Steffener, Reuben, Rakitin, & Stern, 2011). Taken together, this evidence demonstrates the effectiveness in using proxies to measure cognitive reserve in younger adults.

Evidence using event related potentials (ERP) has also demonstrated a negative correlation between proxies for CR and performance related measures in younger adults. Twenty five young adults and 21 older adults took part in a verbal recognition memory task with three levels of difficulty whilst the P300b ERP component was being monitored (Speer & Soldan, 2015). Proxies for CR were gained by measures of reading, vocabulary, and verbal intelligence. The initial results validated the use of the P300b component with an increase in amplitude and a decrease in latency related to an increase in task demand. Importantly, in young and old participants, a negative correlation between CR and the degree of the changes decreased. This suggests an association between increased neural efficiency and measures of cognitive reserve.

5.1.6.2 Measuring cognitive reserve

As some of the previously described studies have demonstrated, education had been a widely used proxy of CR. However, CR and intelligence are distinct. The latter is a measure of purposeful and rational thinking and as such relating to behaviour. Cognitive reserve, on the other hand, relates to a capacity in terms of a buffer, the size of which is relative to an individual's ability to withstand cognitive decline (Nucci, Mapelli, & Mondini, 2012). As such, there is increasing recognition of the separate contribution of other environmental factors of cognitive reserve. These include occupation (e.g. Garibotto et al., 2008; Staff, Murray, Deary, & Whalley, 2004) and leisure activities (e.g. Scarmeas & Stern, 2010; Scarmeas et al., 2003; Solé-Padullés et al., 2009). Therefore, in order to acquire a global measure of CR, levels of both occupation and leisure activities need to be taken into account.

Whilst studies have already measured the contribution of factors beyond intelligence when measuring CR (Solé-Padullés et al., 2009; Valenzuela & Sachdev, 2007), only a couple of questionnaires have attempted to standardise the contribution that these factors make and combine them into a single measure. Currently, the Cognitive Reserve Questionnaire (CRQ; Rami et al., 2011) , the Cognitive Reserve Scale

(CRS; León, García-García, & Roldán-Tapia, 2014), and the Cognitive Reserve index Questionnaire (CRiQ; Maiovis, Ioannidis, Nucci, Gotzamani-Psarrakou, & Karacostas, 2015; Nucci et al., 2012) are three measures that take into account various aspects of the individuals lifestyle. However, with only eight items and application to primarily Spanish or Portuguese populations, the validity of the CRQ if applied to an increased population was unknown. The CRS questions are divided into four different categories. These are daily living, training, hobbies, and social life. Participants are required to answer each of the twenty-four items in the questionnaire according to which ever one of three different life stages that they belong to. Furthermore, an additional period, called late adult-hood is included for the elderly. Given that different sets of questions in the CRS had to be given to participants based on their age, the CRiQ was considered to be easier to administer since it instead relied on an algorithm which takes into account the participants age when calculating answers regarding the frequency of taking part in the number of different leisure and lifestyle related activities. Furthermore, occupational attainment as well is years of education and training are also included in this twenty item questionnaire. Modest reliability of the CRiQ (Cronbach’s $\alpha = 0.62$, 95% CI: 0.56–0.97) may be due to lower years of education in older adults compared to normative scores any other sections (Nucci et al., 2012). Furthermore, this questionnaire has been used successfully in a number of studies for which a measure of cognitive reserve via multiple proxies is required (e.g. Brambilla, Manenti, Ferrari, & Cotelli, 2015; Chillemi et al., 2015; Maiovis, Ioannidis, Nucci, Gotzamani-Psarrakou, & Karacostas, 2015). The lack of pre-screening and categorisation required together with a relatively short twenty items, meant that the CRiQ was the questionnaire of choice for this study.

5.2 Study I

5.3 Method

5.3.1 Design

This study had two parts. First, participants were required to fill out a questionnaire. The second part of the study consisted of a Stroop task. This part of the study had one independent variable. This was the congruence of the stimulus, with levels congruent, incongruent, and neutral. Aside from overall reaction times for each individual, three measures were calculated from latencies in the three different conditions. The first two represented different baselines related to colour naming. The Stroop effect and Stroop interference were calculated by either subtracting latencies from congruent and neutral conditions respectively from the incongruent condition latencies. The Stroop effect is the longer time taken to identify an incongruent word compared to the other conditions due to the need to inhibit the prepotent response of reading the word (Macleod, 1991). Stroop facilitation was calculated by subtracting congruent condition latencies from those gained from the neutral condition.

5.3.2 Participants

One hundred and six healthy adult participants were used in voluntarily took part in the study (92 females, 15 males). Participants had a mean age of 38.57 years (SD = 10.29) with a good distribution over the age range (Figure 5.1). All participants were final year undergraduate students at the Open University, and thus they had already studied in the UK for at least six years. Prior to this had attained a university level of

English language and comprehension to undertake the course. Within the sample, there were a total of 70 participants who consider themselves to have learned more than one language. Of these, 18 practised a second language more than once a week. Within the bilingual sample, L2 was made up of a number of different languages including French, Spanish, Polish, and Italian. For the large majority of participants, English was their first language. There were six participants for whom English was considered L2. This, and the individual nature of Open University study meant that participants were more like to have SLC status.

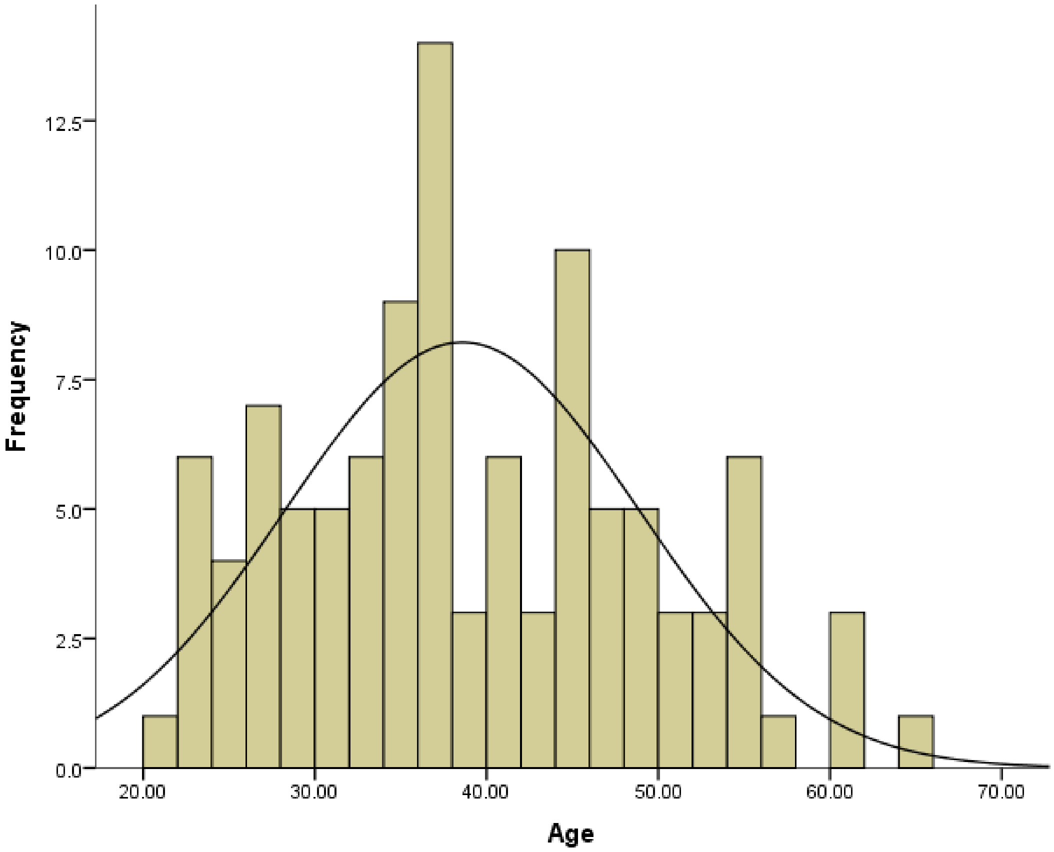


Figure 5.1: Age distribution of participants in study I.

5.3.3 Procedure

Participants were approached during their time at a residential school and asked if they wanted to take part in a study with regards to cognitive reserve and performance. If, after a brief description of cognitive reserve, the participant gave verbal consent, they were taken to an experimental room. After informed consent was provided, the participant engaged in an interview type dialogue with the researcher during which time the questionnaire was completed. The questionnaire provided to the participants composed of forty questions (Appendix B). The first section of the questionnaire asked for demographics. The rest of the questionnaire comprised of two different measures, one of bilingual ability and the other was a measure of cognitive reserve. To date, an established way of measuring the extent of bilingualism in an individual is not available. This may be due to the different demands for different research requirements. For the purposes of this study, an assessment of bilingualism used by Bak, Nissan, Allerhand, & Deary (2014) was deemed appropriate. Participants were asked the amount of languages used and when they started using them. Further, they were also asked how often the languages were used (daily/weekly/monthly/less than a month/never) and in which of three domains. These were conversation, reading, and media. For the primary investigation, bilingual participants were those who reported having a second language with strong bilinguals recording that they used their second language on a weekly basis. In order to evaluate the second language capabilities of all participants a ‘language score’ was derived. This took into account all of the circumstances reported when the individual used their additional language with an additional weighting for using additional language in conversation. This was calculated due to the increased conflict required for language selection in spoken language (Bialystok, 2008). This score was calculated for all participants with zero indicating exclusive monolingual language use. Cognitive reserve was measured by including items from the ”Cognitive Reserve Index Questionnaire” (CRIq; Nucci, Mapelli, & Mondini, 2012). A number of factors from three separate domains were used to calculate an overall score to measure cognitive reserve in an individual. Items relating to sport, leisure, and culture which were carried out over the adult lifespan of an individual were combined to calculate the score.

After completing the questionnaire, the participant was shown to a PC which was running a version of the classic Stroop test (Stroop, 1935). The version of the classic Stroop task used in this experiment was programmed in Eprime 2.0 experimental software (2012). Participants were required to name the colour of the spelled words ‘Blue’ and ‘Red’ as well as the string of symbols “&&&&”. The colour of the words ‘blue’ and ‘red’ were either matched to the word itself (congruent condition) i.e. the word ‘blue’ in the colour blue or the words were in a colour that did not match their meaning (incongruent condition) i.e. the word ‘blue’ in the colour blue. Participants were given the opportunity to practice the task by first undertaking one practice block in which all of the trials were congruent. A second practice block gave the participant an opportunity to practice incongruent trials before the experiment started properly. The participant was then presented with 192 trials of which 128 were neutral with the remainder an even split between congruent and incongruent trials. At the beginning of each trial, a fixation cross was presented in the middle of the screen for 1000ms. This was then followed by the presentation of the stimulus. The stimulus duration was 1000ms or until a response was provided by the participant using the PC keyboard. The mapping of the colours to the response keys was counterbalanced. After this part of the experiment, the participant was fully debriefed and thanked again for their time.

5.4 Results

Two, 2*3 mixed factor ANOVAs were performed on the reaction times, cropped at RT > 200ms. The first factor was individuals who had stated that they had an additional language (n=70) versus those who did not (n=36), therefore this analysis covered all of the participants questioned. The second factor was the Stroop trial type which was either congruent, incongruent, or neutral. The results demonstrated a main effect for additional language (F, (1,104) = 12828.72, p<.05, η^2= .05) and a strong significant main effect for the Stroop measures (F, (2,208) = 11309.48, p<.001, η^2= .99). However, there was no interaction between additional language and Stroop measures (F, (2,208) = 2.12, p=.82, η^2= .02). When the bilingual group was reduced to strong bilinguals who reported speaking a second language on a weekly basis (n=18), the results were similar for Stroop measures (F, (1,51) = 3115.44, p<.001, η^2= .98). However, the main effect of additional language was not significant (F, (1,51) = 2.05, p=.16, η^2= .05) as well as the interaction between additional language and Stroop measures (F, (1,51) = 1.694, p=.16, η^2= .03).

The same tests were then carried out on reaction times. For the entire sample divided to whether or not they stated they had an additional language, there was a significant effect of Stroop measures (F, (2,208) = 41.52, p<.001, η^2= .29), no significant main effect of additional language (F, (1,104) = 0.17, p=.68, η^2= .002). Furthermore, there was no significant interaction between additional language and Stroop measures (F (2,208) = .99, p=.32, η^2= .01). When monolinguals versus strong bilinguals were explored, the results were the same with the main effect of Stroop measures remaining significant (F, (2,102) = 15.91, $p<.001$, $\eta^2 = .24$). Furthermore, non-significant effects were found for the main effect of additional language (F, (1,51) = 0.42, p=.52, $\eta^2 = .01$) and the interaction between additional language and Stroop measures (F, (1,51) = .17, p=.48, $\eta^2 = .003$).

Given the suggestion that the relationship between bilingualism and cognitive reserve may be confounded by educational status (Alladi et al., 2013), tests were carried out to investigate the relationship between the two. An independent samples t-test was carried out between those participants who considered themselves to have an extra language and those who did not. The result was not significant (t (104) = -.13, p= .89, *d* = .03). Furthermore, the same test was carried out between those participants who had not had any experience whatsoever of speaking a second language (n=35) and strong bilinguals who practiced their second language and least once a week (n=18). The results demonstrated no significant difference in years of education between the two (t (51) = 0.93, p = .36, *d* = .27). This finding was also reflected when all participants were taken into account when calculating the relationship between language scores and years of education (r = -.05, N = 106, p = .62). Since items in the CRIQ relate to educational attainment, the relationship between CRIQ scores and language scores was explored. The results demonstrated a non-significant relationship between CRIQ scores and language scores (r = .05, N = 106, p = .32).

Table 5.1: Descriptive statistics of variables central to study I analysis.

	Mean	**S.D.**	**N**
Stroop Effect	27.40	40.40	106
Stroop Interference	31.02	44.71	106
Stroop Facilitation	4.84	25.02	106
CRIQ	112.85	14.54	106
Years of Education	16.45	3.57	106
Language Score	166.13	241.58	106

To confirm the robustness of the Stroop effect, a paired-samples t-test compared facilitation and interference scores. The results demonstrated a significant increase in latency for Stroop interference (t (105) = 6.984, p<.001, *d* = .75). Two series of Independent samples t-tests were carried out. Firstly, comparison between those who consider themselves to have an additional language and those who did not was made (Table 5.2). Secondly, an independent samples t-test was carried out on relevant Stroop scores between those participants who were designated as strict monolinguals and those who were practising bilinguals (Table 5.3). The results from both sets of tests demonstrated no significant difference on any of the Stroop-related measures between monolingual and bilingual groups.

Table 5.2: Results of independent t-tests calculated between those participants who considered themselves to have a second language and those who did not.

	t	df	Sig.
Stroop Effect	.73	104	.47
Stroop Interference	.10	104	.92
Stroop Facilitation	-.10	104	.32
Overall Stroop	.41	104	.68

Table 5.3: Results of independent t-tests calculated between strict monolinguals and bilinguals on measures of Stroop performance.

	t	df	Sig.
Stroop Effect	.50	51	.62
Stroop Interference	-.01	51	.99
Stroop Facilitation	-.72	51	.48
Overall Stroop	-.65	51	.52

A series of multiple regressions were calculated out to investigate the predictive ability of scores from the CRIQ and the scores related to multilingual use predicted performance on a number of aspects in the Stroop task.

5.4.1 The Stroop Effect

An analysis of standard residuals was carried out, which showed that the data contained no outliers (Std. Residual Min = -1.38, Std. Residual Max = 3.09). Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (CRIQ Scores, Tolerance = .998, VIF = 1.002; Language Score, Tolerance = .998, VIF = 1.002). Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 1.72). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points were close to the line. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. The data also met the assumption of non-zero variances (CRIQ Scores, Variance = 211.39; Language Scores, Variance = 58362.08; Stroop Effect, Variance = 1632.09). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to the Stroop effect ($F(2, 100) = 1.04$, $p = .36$, $R^2 = .02$, $R^2_{\text{Adjusted}} = .00$). The analysis shows that CRIQ scores level did not significantly predict Stroop effect scores ($\beta = 0.10$, $t(102) = 1.00$, $p = .32$). Further, language scores failed to significantly predict Stroop effect scores (Beta = -0.11, $t(102) = -1.08$, $p = .28$).

5.4.2 Stroop Interference

One outlier was removed when the analysis of standard residuals was carried out. This was removed and run again. A further outlier was removed and it was found that the standard residuals were acceptable (Std. Residual Min = -1.72, Std. Residual

Max = 3.18). Previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 1.62). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points were reasonably close to the line. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. Stroop interference, in addition to the other variables previously described, met the assumption of non-zero variances (Stroop Interference, Variance = 1366.35). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to Stroop interference (F(2, 98) = 0.23, p = .79, $R^2 = .00$, $R^2_{\text{Adjusted}} = -.02$). Taken individually, the analysis shows that CRIQ scores level did not significantly predict Stroop interference scores (β= 0.06, t(100) = 0.55, p=.58). Further, language scores failed to significantly predict Stroop interference (Beta = -0.04, t(100) = -0.42, p=.68).

5.4.3 Stroop facilitation

An analysis of standard residuals was carried out, which showed that the data contained two initial outliers. This was removed and run again. A further outlier was removed until the standard residuals were acceptable (Std. Residual Min = -2.32, Std. Residual Max = 2.31). As with stroop interference, previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 1.98). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points followed the line to a good degree. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. Stroop facilitation, in addition to the other variables previously described, met the assumption of non-zero variances (Stroop facilitation, Variance = 429.87). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to Stroop facilitation (F(2, 97) = 0.87, p = .42, R^2 = .02, $R^2_{Adjusted}$ = -.00). Both CRIQ scores (β= -0.02, t(99) = -0.19, p=.85) and language scores failed to significantly predict Stroop interference (Beta = 0.13, t(99) = 1.31, p=.19).

5.4.4 Overall RT

An analysis of standard residuals showed that the data contained an initial outlier. This was removed and run again revealing acceptable standard residuals (Std. Residual Min = -1.77, Std. Residual Max = 2.25). Previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. The data met the assumption of independent errors (Durbin-Watson value = 1.67). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points were acceptably close to the line. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. Overall reaction times met the assumption of non-zero variances (Overall reaction times, Variance = 4005.26). Once again, the enter method was used for the regression. The results demonstrated that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to overall reaction times (F(2, 99) = 0.32, p = .72, R^2 = .01, $R^2_{Adjusted}$ = -.01). CRIQ scores level did not significantly predict overall reaction times (β= 0.06, t(101) = 0.59, p=.56). Further, language scores failed to significantly predict overall reaction times (Beta = 0.05, t(101) = 0.52, p=.61).

Table 5.4: Summary of ANOVA results of regression between CRIQ and language scores and dependant variables relating to Stroop performance.

	F-value	**df**	**p**	**R^2**	**$R^2_{Adjusted}$**
Stroop Effect	1.04	2,100	.36	.02	.00
Stroop Interference	0.23	2,98	.79	.01	-.02
Stroop Facilitation	0.87	2,97	.42	.02	-.00
Overall RTs	0.32	2,99	.72	.01	-.01

Table 5.5: Summary of individual contributions of CRIQ scores and language scores on overall RTs.

	CRIQ scores				Language scores			
	β	**t**	**df**	**p**	**β**	**t**	**df**	**p**
Stroop Effect	0.10	1.00	102	.32	-0.11	-1.08	102	.28
Stroop Interference	0.06	0.55	100	.58	-0.04	-0.42	100	.68
Stroop Facilitation	-0.02	-0.19	99	.85	0.13	1.31	99	.19
Overall RTs	0.06	0.59	101	.56	0.05	0.52	101	.61

5.5 Study II

5.6 Method

5.6.1 Participants

Ninety eight healthy adult participants voluntarily took part in the study (78 females, 20 males). Mean age = 29.59 S.D. = 9.67, age range 19-65. Participants were students at Birkbeck College, University of London. Participants were from a variety of linguistic backgrounds but were all required to pass English language at International English Language System (IELTS) level 6.5. Participants were second year students taking part in a research methods class. DLC and SLC status in those bilingual students within the sample was mixed with some students existing within social groupings/study groups which contained members who spoke the same language and therefore switches between English and heritage language (HL) was common.

5.6.2 Procedure

As per the previous study, participants were required to complete a questionnaire. The second part of the study consisted of a task switching task. This part of the study had one independent variable, whether the following task requirement was the same or different to the previous trial. The experiment had two conditions which reflected this. Participants were recruited during a psychology research methods class. Upon consenting to take part in the study they were provided with the amalgamated questionnaire, which included demographic information, a language use questionnaire and the CRIQ. After completing the questionnaire, the participant was taken to a room which included a PC, upon which was the second part of the experiment, the task switching experiment was conducted. The behavioural task in this study consisted of a task switching task (Kessler & Meiran, 2010). The experiment was programmed using E-prime experimental software (2012). The task required participants to sort a presented shape according to one of two criteria, these were either by the colour of the shape or by the shape itself. The stimuli consisted of a blue and a red version of a circle and a triangle, making a total of four separate shapes presented sequentially to the participant. During the experiment a blank slide was presented to the participant for 500ms, this was followed by a cue word which was either ‘COLOUR’ or ‘SHAPE’ in white Courier new, at 18 point size, presented for 600ms in the centre of the screen. Finally, a single shape was presented to the participant (Figure 5.2). Depending on the cue provided to the participant, they were either required to press the ‘X’ key on the keyboard if the colour of the shape was blue or ‘M’ if the shape was green. Alternatively, if the participant was required to sort the shape according to its shape, the participant was required to press ‘X’ if the shape was a circle or ‘M’ if it was a triangle. All slide backgrounds were black. At presentation of the shape, a time duration of 2000ms was given for the participant to respond. If no response was provided, an error was logged. The experiment consisted of five blocks of sixty trials. Each block consisted of 30 repeat trials in which the same task cue was repeated e.g. shape followed by shape, and 30 switch trials in which a task cue was followed by a different cue e.g. Shape followed by colour. After taking part in the behavioural study, participants were debriefed and thanked again for their time.

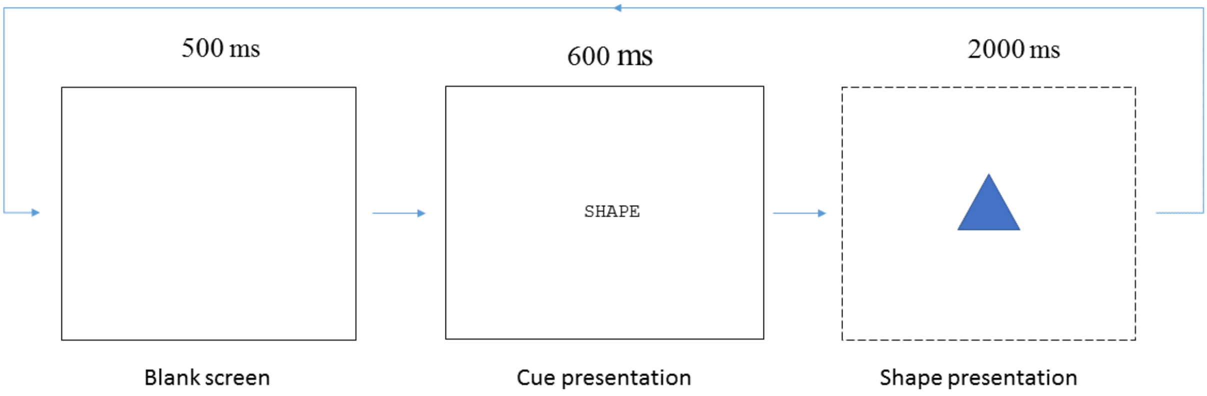


Figure 5.2: Timeline of events occurring in each trial for the task switching experiment.

5.7 Results

Due to the large number of bilinguals within the sample, it was decided to expand the criteria for a monolingual to an individual who may have stated that they had an additional language but had answered ‘never’ when questioned about the times this was practiced. Therefore, the following analysis were based on strong bilinguals (n=47) and monolinguals who fulfilled the above criteria (n=28). Firstly, an independent samples t-test was carried out between bilinguals and monolinguals (n=28) on educational status to see if there was a difference between the two groups (Alladi et al., 2013). The results demonstrated no significance between the two (t (51) = 0.61, p = .55). This was further confirmed by the calculation of a non-significant relationship between language scores, which took into account all levels of multilingual ability, and years of education (r = .11, n = 94, p = .28). As with study one, the relationship between the CRIQ scores and language scores was also tested. This was non-significant (r = .05, n = 103, p = .64).

Table 5.6: Descriptive statistics of variables central to study II analysis.

Variable	**Mean**	**S.D.**	**N**
Overall RT	733	155	98
Switch trials (RT)	767	170	98
Repeat trials (RT)	699	149	98
Switch cost	68	68	98
CRIQ	101.46	11.92	98
Years of Education	15.13	3.27	96
Language Score	209.10	232.86	96

A 2*2 mixed ANOVA was then carried out on the task switching reaction times with additional language (monolingual or bilingual) as one factor and trial type in terms of switch and repeat trials was carried out. The results demonstrated a non-significant main effect for type (F (1,75) = 69.57, p<.001). There was no significant effect for language (F (1,75) = .303, p=.58) and a significant interaction between additional language and trial type (F (1,75) = 69.57, p<.001). Independent sample t-tests were also performed between individuals who stated that they were practicing bilinguals (n=47) and monolinguals according to the previous description (n=28).

Table 5.7: Results of independent t-tests calculated between strong monolinguals and bilinguals on measures of task switching performance.

	t	df	Sig.
Overall RT	-.55	75	.58
Switch trials (RT)	-.71	75	.48
Repeat trials (RT)	-.34	75	.74
Switch cost	-1.08	75	.52

A series of multiple regressions were calculated to investigate the predictive ability of scores from the CRIQ and the language scores, which were applied to all participants, on aspects of task switching performance.

5.7.1 Switch cost

An analysis of standard residuals was carried out, which showed that the data contained one outlier. This was removed and the analysis was recalculated whereupon no further outliers were found (Std. Residual Min = -2.00, Std. Residual Max = 2.76). Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (CRIQ Scores, Tolerance = .97, VIF = 1.03; Language Score, Tolerance = .97, VIF = 1.03). Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 2.26). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points were reasonably close to the line. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. The data also met the assumption of non-zero variances (CRIQ Scores, Variance = 142.30; Language Scores, Variance = 54223.11; Switch cost, Variance = 4633.23). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to the switch cost (F(2, 92) = 1.38, p = .26, R^2 = .03, R^2_{Adjusted} = .01). Taken individually, the analysis shows that CRIQ scores level did not significantly predict switch cost scores (β= -0.16, t(94) = 1.54, p=.13). Further, language scores failed to significantly predict switch cost scores (β = -0.04, t(94) = -.33, p=.74).

5.7.2 Switch trial RT's

An analysis of standard residuals demonstrated that standard residuals were acceptable (Std. Residual Min = -2.19, Std. Residual Max = 2.51). The previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 1.76). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors with points following the line closely in the normal P-P plot of standardised residuals. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. Switch trial RTs, in addition to the other variables previously described, met the assumption of non-zero variances (Switch trial RTs, Variance = 29100.96. Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to Switch trial RTs ($F(2, 93) = 1.29$, $p = .28$, $R^2 = .03$, $R^2_{\text{Adjusted}} = -.01$). Taken individually, the analysis shows that CRIQ scores level did not significantly predict Switch trial RTs ($\beta = -0.10$, $t(95) = -.92$, $p = .36$). Further, language scores failed to significantly predict Switch trial RTs ($\beta = 0.15$, $t(95) = 1.46$, $p = .15$).

5.7.3 Repeat trial RTs

Standard residuals were acceptable according to analysis (Std. Residual Min = -1.99, Std. Residual Max = 2.41). As with Switch trials, previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. Furthermore, the data met the assumption of independent errors (Durbin-Watson value = 1.69). The histogram of standardised residuals indicated that the data contained normally distributed errors, with the normal P-P plot of standardised residuals following the line. The scatterplot of standardised predicted values demonstrated that the data met the assumptions of homogeneity of variance and linearity. The assumption of non-zero variances was met (Repeat trial RTs, Variance = 21402.42). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to repeat trial RTs ($F(2, 93) = 1.02$, $p = .37$, $R^2 = .02$, $R^2_{\text{Adjusted}} = -.00$). Taken individually, the analysis shows that CRIQ scores level did not significantly predict repeat trial RTs ($\beta = -0.04$, $t(95) = -0.35$, $p = .72$). Language scores also failed to significantly predict repeat trial RTs ($\beta = 0.15$, $t(95) = 1.42$, $p = .16$).

5.7.4 Overall RTs

An analysis of standard residuals demonstrated no outliers and revealed acceptable standard residuals (Std. Residual Min = -2.15, Std. Residual Max = 2.38). Previous analysis demonstrated the same acceptability of collinearity for CRIQ and language scores. The data met the assumption of independent errors (Durbin-Watson value = 1.72). The histogram of standardised residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardised residuals, which showed that points were close to the line. The scatterplot of standardised predicted values showed that the data met the assumptions of homogeneity of variance and linearity. Overall RTs met the assumption of non-zero variances (Overall RTs, Variance = 24093.25). Using the enter method it was found that CRIQ scores and language scores did not explain a significant amount of the variance in the performance with regard to overall reaction times ($F(2, 93) = 1.17$, $p = .31$, $R^2 = .03$, $R^2_{Adjusted} = .00$). Taken individually, the analysis shows that CRIQ scores level did not significantly predict overall RTs ($\beta = -0.07$, $t(95) = -.67$, $p = .50$). Further, language scores failed to significantly predict overall RTs ($\beta = 0.15$, $t(95) = 1.48$, $p = .14$).

Table 5.8: Summary of ANOVA results of regression between CRIQ and language scores and dependant variables relating to task switching performance.

	F-value	df	p	R^2	$R^2_{Adjusted}$
Overall RT	1.17	2,93	.31	.03	.00
Switch trials (RT)	1.29	2,93	.28	.03	.01
Repeat trials (RT)	1.02	2,93	.37	.02	.00
Switch cost	1.38	2,92	.26	.03	.01

Table 5.9: Summary of individual contributions of CRIQ scores and language scores on measures of task switching performance.

	CRIQ scores				**Language scores**			
	β	**t**	**df**	**p**	**β**	**t**	**df**	**p**
Overall RT	-0.07	-0.67	95	.50	0.15	1.48	95	.14
Switch trials (RT)	-0.10	-0.92	95	.36	0.15	1.46	95	.15
Repeat trials (RT)	-0.04	-0.35	95	.73	0.15	1.42	95	.16
Switch cost	-0.16	-1.54	94	.13	-0.04	-0.33	94	.74

5.8 Discussion

Two large-scale experiments were carried out to further investigate the relationship between multiple language use, CR and executive control. Measures of CR were taken by an established cognitive reserve questionnaire, the CRIQ, which provides a measure of cognitive reserve according to more traditional proxies of the phenomena as well as a measure of multiple language use. Language was measure using a multilingual questionnaire. In terms of executive control processes, two large separate groups of participants were used and tested with one of two different measures, the Stroop task or a computerised version of the dimensional task switching task. The former was a test requiring inhibitory processing, the latter was a measure of task switching. With around 100 participants and the two predictor variables, these studies were powerful enough to detect an effect size (f^2) of around 0.2 with a statistical power of 80% (1-β).

The results from the first experiment in which inhibition was investigated using the Stroop task demonstrated no difference between monolinguals and strong bilinguals in terms of their level of education. Furthermore, using language scores which took into account all participants, no relationship was found between the scores and years of education. A number of regression analyses, each one using a different measure of Stroop test performance, were performed. These demonstrated no predictive relationship between CRIQ scores and language scores in predicting overall reaction times, Stroop inhibition, Stroop facilitation and the Stroop effect as the dependent variables. One significant result to arise from this analysis was from a mixed factor ANOVA carried out on the Stroop accuracy scores in which the bilingual category was expanded to include individuals who had simply stated that they had an additional language. This analysis showed a significant difference between monolinguals and bilinguals but no difference was found when strong bilinguals only were used.

Given the similarity in effect size, the reduction in participant numbers due to filtering out strong bilinguals may have caused the difference in results. However, the wider group of bilinguals included those with very limited experience in a second language which may suggest that limited contact may be enough to elicit some differences in executive control.

The results from the computerised dimensional sorting experiment, which investigated the contribution that CRIQ scores and language scores made to predicting task switching performance, followed those of the first experiment. Firstly, comparison between monolinguals and bilinguals revealed no significant difference in levels of education. Furthermore, this was reinforced by a lack of relationship between language scores and years of education. Several regression analysis were carried out, all of which revealed no significant ability to predict measures of task switching performance. Both CRIQ and language scores did not significantly predict Switch cost, overall RTs or the reaction times from Switch trials and repeat trials independently.

The current results present interesting implications for the aims of this study. One of the primary aims of this study was to investigate the relationship between bilingualism/multilingualism and executive control processes given the more recent findings that have demonstrated no effect for this relationship. The results of this investigation have supported those studies which had been carried out more recently and demonstrated a lack of effect in tasks requiring task switching (Prior & MacWhinney, 2010) and a more specific inhibitory processing with the Stroop task (Kousaie & Phillips, 2012). This was shown both with a simple comparison between those individuals who would be considered monolinguals and bilinguals in the strictest sense as well as regression analysis using the language score which took into account all participants.

A second aim of this study was to examine the relationship between performance in executive control tasks and measures of cognitive reserve using the CRIQ. This was motivated by the comparative lack of evidence as to which cognitive functions are strengthened by environmental proxies of cognitive reserve such as years of education and lifestyle, as measured by the questionnaire. The results provided by regression analysis with CRIQ scores as the predicting variable demonstrated no significant relationship between this factor and both Stroop performance and task switching performance.

Two explanations can be provided with regards to the lack of association between cognitive reserve, as measured by the CRIQ and scores on the Stroop and task switching experiments. The theoretical reasoning behind this result is that those factors which have been demonstrated to have an association with the offset of cognitive decline in older adults (Scarmeas et al., 2006; Scarmeas & Stern, 2003) are not manifest in the specific cognitive performance differences. Studies that have explored bilingualism and executive control performance in older adults are self-fulfilling in that they use bilingualism rather than other measures of cognitive reserve (e.g. Bialystok, Craik, Klein, & Viswanathan, 2004). Therefore, it may not be the strengthening of existing cognitive processes, as in neural reserve, that confer a cognitive advantage in later life of adults who score highly on such measures. An alternative suggestion would be that the additional brain substrate associated with bilingual individuals (Abutalebi, Guidi, et al., 2015; Abutalebi, Canini, et al., 2015) acts as a biological buffer with non-specific cognitive functioning. This relates back to the older theory of passive Brain Reserve (Satz, 1993). Furthermore, the results suggest that reserve gained via proxies such as additional years of education or active lifestyle is truly a reserve which only becomes relevant when neural resources are being depleted.

An alternative suggestion to the lack of relationship between scores on the CRIQ questionnaire and performance in executive control tasks is that questionnaires measuring CR are not yet mature enough to be considered highly valid. Full validation of the questionnaire such as the CRIQ would more require longitudinal studies relating scores to behavioural measures of cognitive competence over age. While some cross-sectional studies have found relationships between measures of the CRIQ and cognitive efficiency in older adults (Mondini et al., 2016), only time will provide clear longitudinal data. Furthermore, a negative relationship between scores in the CRIQ and brain activation (processing effort) would complete the correlative triad.

What this study also demonstrates is that there is a lack of relationship between bilingualism and education. Analysis comparing bilinguals with non-bilinguals demonstrated a lack of significant difference on independent measures of years of education. Furthermore, the lack of relationship between scores for the CRIQ and language scores negates the suggestion that bilingualism is simply a covariate of the years of education an individual had accrued. The results of the current study demonstrate this relationship to be unsupported, meaning that bilingualism should be a factor which is studied in its own right in relation to cognitive reserve. In summary, the theoretical relationship between the cognitive reserve and language questionnaires is not assured. This would only be the case if multiple language use was a result of high educational attainment. The results of both studies in this chapter have demonstrated that this suggestion is not supported.

The lack of predictive power of language scores in relation to both the Stroop test and task switching supports a number of more recent studies which question the effect of multilingualism on executive processing. Specifically, the results of the regression analysis with regards the Stroop test place a lack of effect for multilingualism for younger adults between studies which have demonstrated no effect of bilingualism older adults (Kousaie & Phillips, 2012) as well as schoolchildren (Duñabeitia et al., 2014). Furthermore, this study supports previous research which has shown no difference between monolinguals and bilinguals in relation to task switching abilities (Hernández et al., 2013; Paap & Greenberg, 2013; Paap et al., 2015). Conversely, the results of this study did not support those investigations that have found a relationship between bilingualism and executive control (Bialystok, 2011; Bialystok et al., 2004; Martin-Rhee & Bialystok, 2008).

Given the gulf between studies demonstrating a bilingual benefit and those which do not, of which the current study mostly belongs, reconciliation may come in two forms. The first will be to investigate further the suggestion made by Bialystok et al. (2008), that, put simply, bilingualism does affect executive control but the specific processes within executive control are not fully defined. Therefore, in measuring inhibition with a Stroop task and task switching with a task switching task, this study may have been measuring overlapping processes but not those that were specifically strengthened with bilingualism. What is unclear, however, is why the previous results supporting a bilingual advantage were found in some studies which included traditional measures of executive control. The answer may have something to do with the population being used, which leads on to the second point. The second strand of future research should involve those external aspects which could not be controlled in the current studies. Namely, the frequency at which an individual switches between first and second languages (Hartanto & Yang, 2016) and the nature of the languages themselves (Tao et al., 2015).

One further strand of enquiry may come at a different level of investigation. Namely, genetic differences behind each of the specific populations which have demonstrated clear differences between monolinguals and bilinguals. A preliminary study by Hernandez, Greene, Vaughn, Francis, & Grigorenko (2015) had established a gene variation which was responsible for individual differences in cognitive flexibility. Furthermore, in their sample of 122 Spanish – English bilinguals and English monolinguals, 69% of the bilinguals carried the ANKK1 gene compared to only 31% of the monolinguals. One of the major questions that this study presents is the reason for this distribution of the specific gene. However, these initial findings suggest a previously unbeknownst reason for variability in the results of different studies.

Whilst the results of this study do not support the relationship between bilingualism or multilingualism and executive control, it must be remembered that executive control was only the clue to how cognitive reserve substantiates itself. What the results of this experiment and other recent experiments have suggested is that cognitive reserve, as measured by both bilingualism and proxies other than multiple languages, do not have their genesis in executive control. What this suggests is that the time has come to look for other explanations of the relationship between bilingualism and neural reserve. One of the areas that may prove fruitful is that of imaging studies. Some additional evidence for a relationship between bilingualism and neural reserve which bypasses a bilingual advantage based explanation comes from a recent DTI study that has demonstrated that rather than regions related to executive control, lifelong bilingualism appears to have an effect on white matter integrity (Gold, Kim, Johnson, Kryscio, & Smith, 2013).

5.9 Conclusion

Over the course of the experiments in this chapter being carried out, there have been a growing number of studies demonstrating no effect for multilingualism upon executive processing. However, studies investigating the relationship between multilingualism and cognitive reserve have demonstrated robust results. This study calls into question two aspects of language in cognitive reserve. Firstly, this study aligns itself with those investigations and commentaries which have found no support for the bilingual advantage. Secondly, it appears that neural reserve, as measured by other proxies does not have its foundations in executive processing. The conclusion made by the review and investigations carried out in this chapter is that cognitive reserve cannot refer back to its purest definition in that it is really only useful as a resource when age-related biological decline is manifest.

Chapter 6: Discussion

6.1 Overview

The studies in this thesis cover two different aspects of cognitive reserve. The first aspect is neural compensation. This refers to the suggestion that the cognitive function underpinned by declining neural substrate can be supported by another region of neural substrate not normally associated with the function (Steffener et al., 2011; Stern, 2003, 2009). Neural compensation is covered in chapters two and three. In these two chapters, two different methodological perspectives are taken. In chapter two, a biologically inspired computational model is produced that suggests a mechanism which would enable interhemispheric processing, in accordance with a compensatory view of the HAROLD model (Cabeza, 2002). Chapter three presents a behavioural study which explores whether or not neural compensation across hemispheres is an age invariant phenomena.

The second aspect of cognitive reserve, neural reserve, relates to a buffer against cognitive decline produced by the strengthening of existing neural pathways (Steffener et al., 2011; Stern, 2009). Chapters four and five cover this aspect of cognitive reserve in specific relation to bilingualism, a proposed factor in increasing cognitive reserve. As with neural compensation, two methodological perspectives are taken. Chapter four presents a neural network model of monolingual and bilingual language learning in order to explore representational spacing in relation to bilingualism. Chapter five presents two large studies which explore the bilingual advantage and its relationship with cognitive reserve and executive control.

6.2 A computational model of neural compensation

The model in chapter two explored the concept of cognitive reserve and presented a potential mechanism for opening a processing channel between both hemispheres based on the subjective task load of an individual. In doing so, this model aimed to explain the observed benefit of the bilateral activation demonstrated in older adults when carrying out some cognitive tasks (Reuter-Lorenz & Cappell, 2008). The model used the functionality described from two neural regions, the Anterior Cingulate Cortex (ACC) and the rostral PreFrontal Cortex (rostral PFC). The contribution of the ACC was considered for this model due to its involvement in monitoring conflict (Barch et al., 2001) with strong links existing between this and subjective task difficulty (Paus et al., 1998). The rostral PFC was used in the model due to its functionality and involvement in the gateway hypothesis (Burgess et al., 2007). To increase validity of the contribution of both the ACC and rostral PFC, a meta-analysis was carried out on studies which had described activation in both of these areas. The initial meta-analysis demonstrated a positive relationship between activation in the rostral PFC and the ACC. This finding gives some indication of the way in which the two areas were activated together for a particular purpose. A qualitative exploration of the difficulty of the tasks which featured in the meta-analysis showed that both areas increase with task difficulty, giving further credence to the assertion that task difficulty drives neural communication.

The results of the model in Chapter two demonstrated data patterns similar to those shown in a visual field study which presented matching stimuli, either between or within visual hemifields (Reuter-Lorenz et al., 1999). The results also captured a pattern of activity demonstrated in older adults in the imaging literature in which greater bilateral activity is associated with higher performance in older adults (Reuter-Lorenz & Cappell, 2008). The inclusion of the necessary components of this model demonstrate the importance of the role of conflict monitoring in neural compensation. The consistency of the functionality of both the ACC and the rostral PFC throughout the life span suggested that the model itself reflected what might be described as an inherent mechanism, rather than one that might be a specific result of age-related degeneration. Due to its success in predicting the behavioural and imaging results, a tentative prediction was that this mechanism was age invariant. This means that the model reflected a mechanism which could be applied to both younger and older adults. This prediction was in line with the idea of neural compensation as an age-invariant mechanism which was activated by subjective task demand rather than simply by age (Schneider-Garces et al., 2010).

6.3 Investigating the age invariance of across-hemisphere neural compensation

The study in chapter three built on the prediction made in chapter two, that the mechanism that allowed processing across both hemispheres at a given level of task demand is non-exclusive to older adults, meaning that it is age-invariant. Therefore, the bilateral activation observed in older adults in imaging studies (Cabeza, 2002) and the performance gain observed at high task demand when stimuli are matched between hemispheres compared to within hemisphere matches (Reuter-Lorenz et al., 1999) are due to subjective task demand only and is not the preserve of older adults.

The aim of this study was to investigate whether there was an advantage for presenting matching stimuli across hemispheres compared to within hemispheres in younger adults. Changes were made to the visual field paradigm used by a number of researchers (Guzzetti & Daini, 2014; Reuter-Lorenz et al., 1999) in order to create the stimulus set that was deemed sufficiently difficult to produce an across-hemisphere advantage for younger adults. Therefore, using a combination of Arabic and dot based numeric representations, five levels of difficulty were achieved.

The main findings of this study were that younger adults did not demonstrate a crossover from an advantage for within hemisphere matches to across hemisphere matches at higher levels of task demand. The progression of difficulty of the stimuli in the experiment demonstrated a good linear trend. Therefore, the results were not due to the confounding effect of a poorly designed stimulus set. It may be that the stimuli were not difficult enough. However, variability also increased over the progression of task difficulty and it was decided that adding a further computational step would produce such a large variance that any effect would be diluted.

The lack of crossover from a within hemisphere advantage to a between hemisphere advantage at harder levels of task difficulty in younger adults meant that this study supports a picture of neural compensation, at least specific to interhemispheric compensation, which is due to a mechanism that becomes active in older age. Additional validation of this statement would occur with the expected across hemisphere advantage occurring in older adults on exactly the same task, presumably at the lower end of the task demand scale. To conclude a lack of age invariance for interhemispheric compensation contradicts the prediction made from the model in Chapter two and further suggests that age-related reorganisation may drive this change.

If the data from Chapter three were assumed to be correct, it would be prudent to look back to Chapter two with regards to possible reasons why the prediction of the model might be wrong. One of the key assumptions of the model which generated this prediction was the inclusion of two areas of the brain which are known to have involvement in conflict monitoring and processing control, the anterior cingulate cortex and the rostral pre-frontal cortex respectively. Functionality of these two regions is established from studies using younger adults. Therefore, when applied to monitoring task demand and controlling access between hemispheres, this mechanism would be age invariant. An alternative mechanism was explored in Chapter three which involved the degrading of the inhibitory function of the corpus callosum to a point where previously inhibited activation in the contralateral hemisphere was able to contribute to on-task processing. Switching from single hemisphere to dual hemisphere processing may well be age invariant. However, in relation to increased task demand, it may well be that a decline in the inhibition is additionally required to take a break off the contribution of the contralateral hemisphere.

A secondary analysis investigated the laterality of neural compensation. This meant that matches made when the probe was in one hemisphere and the target in another were analysed separately according to which hemisphere the probe was in. Furthermore, comparisons were made between those matches made within hemisphere in the left hemisphere and the right hemisphere. The results of this analysis demonstrated no difference between those between hemisphere trials for which the probe was on the left and the right. However, an interaction was found for within hemisphere trials. This meant that at low levels of task demand, a right hemifield/left hemisphere advantage was observed whereas the opposite was observed at higher levels of task demand. Such a result suggests that rather than additional activation in the contralateral hemisphere, each of the hemispheres was specialised in dealing with easy and difficult processing. However, given the change in the nature of the task to elicit task difficulty, task type may have confounded this effect.

6.4 Neural network models of Bilingualism and Cognitive Reserve

The study in chapter four marked the beginning of the investigation into another aspect of cognitive reserve, neural reserve. This particular aspect of cognitive reserve relates to the reinforcing of cognitive processes by strengthening those neural pathways that underlie them (Stern, 2002). This therefore differs from neural compensation in that it is neural substrate already associated with the cognitive function that provides the buffer against age-related decline (Stern, 2009). The investigation within Chapter four takes a computational approach with the aim of exploring the genesis of neural reserve in relation to one particular proxy of cognitive reserve which is associated with neural reserve, bilingualism.

Two neural network models were created, one monolingual and one bilingual with the purpose of investigating the spacing of representations within the first language of each model. Within both the monolingual and bilingual networks, hidden layer size varied from five, ten, fifteen, and twenty nodes in size, as a reflection of differing amounts of neural substrate in individuals, known as Brain Reserve (BR) (Katzman, 1993; Stern, 2009).

This study was motivated by two factors. The first was the indication that cognitive reserve derived through use of a second language was due to a cognitive advantage in executive control (Olsen et al., 2015). The second factor was that continual recall of similar, and therefore overlapping, representations led to the decline in the ability to do so. This is known as retrieval induced inhibition (Anderson et al., 1994). Given these factors, it was predicted that reduced spacing among representations in the bilingual neural network would lead to the need for greater recruitment of inhibitory mechanisms for correct recall. As such, this continual application and reinforcement of inhibitory processes forms the basis of cognitive reserve in individuals (see: Green, 1997; Johnson & Anderson, 2004; Storm et al., 2015).

The results showed that representations in the bilingual network are more crowded than the monolingual network but still respect the global categorical hierarchy. Furthermore, categories are still delineated in a bilingual environment but appear closer together. Greater amounts of BR, represented by larger hidden layer sizes in the networks, allowed for more representational space. Finally, protection against age-related cognitive decline is conferred if sufficient BR is present in the bilingual environment. With regards to inhibition within the system, examination of the activation of language-related tags in the input set showed that inhibition within the semantic space was conferred as a result of competing activation from the language tags.

6.5 The relationship between language, cognitive reserve and executive control.

The aim of this chapter was to continue the theme of the contribution of language to neural reserve by investigating how bilingualism influences executive processing and whether cognitive reserve as measured by traditional proxies also has its foundations in an executive control advantage. As stated previously, the bilingual advantage appeared to be one of the clues as to the nature of how cognitive reserve is instantiated in bilingual older adults (Bialystok, Craik, & Luk, 2012). However, recent studies have questioned the relationship between bilingualism and increased performance in executive control tasks (e.g. Hernández, Martin, Barceló, & Costa, 2013). Therefore, one of the main motivations of the study in this chapter was to replicate the bilingual advantage in two different executive control tasks with two separate, large samples. Self-reported measures of multilingual use were taken as well as behavioural performance in either the Stroop task or two-dimensional task switching. Furthermore, cognitive reserve, as measured by the Cognitive Reserve Index Questionnaire (CRIQ; Nucci, Mapelli, & Mondini, 2012), was also measured.

Measuring CR according to more traditional proxies such as years of education and lifestyle via the CRIQ was motivated by an additional aim of the study in Chapter five. By measuring the level of CR (via the CRIQ) in the sample, it was possible to investigate whether there was a relationship between traditional proxies (included in the CRIQ) and executive control. A clear relationship between those proxies and CR has been established. However, it is not clear how the neural reserve accrued by proxies measure in the CRIQ are instantiated at a cognitive level (Steffener & Stern, 2012). Therefore, if a significant relationship was established then it might be the case that neural reserve is exclusively the preserve of neural circuitry driving this executive control rather than the result of different proxies reinforcing different cognitive domains.

The results of the study in this chapter demonstrated that there was minimal contribution of additional language use to executive control performance. However, some difference was found in the amount of errors between those who had any experience in a second language and those who had not. This suggested that limited experience was sufficient enough to provide an advantage. Overall, the results appeared to reinforce a message which has been getting louder over recent years, that there is no bilingual advantage. With regards to the lack of relationship between other measures, taken by the CRIQ, and executive processing, it appears that the search still continues for a clear cognitive underpinning of CR.

6.6 Overall Findings

The overall findings of this thesis span the theoretical breadth of cognitive reserve (Stern, 2003, 2009). From the perspective of neural compensation, the research in this thesis has provided an explanation of a mechanism which serves to allow processing of task-related information to occur in both hemispheres should task demand exceed a threshold. This model drew upon the functionality of two distinct brain regions. Both the conflict monitoring functionality of the ACC and the switching ability of the rostral PFC were deemed necessary and sufficient to produce a model which could simulate a pattern of activation demonstrated in behavioural and imaging literature. A meta-analysis of 60 studies demonstrated a significant relationship between activation levels for both of these regions. This suggests that under certain circumstances they may act together towards a specific goal, in this case opening a processing pathway when task demand reaches certain threshold. In addition to providing a feasible model of bilateral activation, the behavioural study suggests that this particular mechanism is the exclusive preserve of older adults. Increasing task demand to high levels in a sample of healthy adults demonstrated no advantage for presenting matching stimuli across the hemispheres.

In terms of neural reserve, the findings in the second half of this thesis focus on the suggestion that rather than a covariate of years of education, bilingualism directly contributes to offsetting cognitive decline. Given the executive control advantages suggested by the bilingual advantage theory, investigations using the monolingual and bilingual neural network model suggest that neural reserve may be instantiated at the cognitive/neural level through the reduction in spacing between representations. This would in turn lead to the need for greater recruitment of inhibitory mechanisms and lead to greater executive control in this domain. However, given the preponderance of recent studies which have demonstrated no effect for bilingualism in executive control (e.g. Hernández, Martin, Barceló, & Costa, 2013; Prior & MacWhinney, 2010; see Hilchey & Klein, 2011 for a review) the relationship between bilingualism and the delayed onset of cognitive decline in older adults may be more direct. This was reinforced by two large-scale behavioural studies which investigated the relationship between bilingualism and executive control performance and found no clear relationship between bilingualism and inhibition and task switching. Furthermore, it appears that neural reserve may have other ways in which it is instantiated than executive control since measuring it by more traditional proxies with the CRIQ (Nucci et al., 2012) revealed no predictive relationship between scores with this measure and inhibition and task switching. Therefore, neural reserve may not have explicit cognitive underpinnings but rather a more general neural underpinning, such as that suggested in the literature pertaining to BR.

6.7 HAROLD

The overall results of this study support the original theory Hemispheric Asymmetry Reduction in Older adults (HAROLD; Cabeza, 2002). The computational model provided viable data, supported by biological evidence, to suggest that a mechanism could exist which might switch between within hemisphere processing to between hemisphere processing if task demand exceeds a specific pressure. Furthermore, the behavioural study carried out in this thesis supported earlier perspectives of neural compensation which suggested that the HAROLD model was compensatory for older adults only (Cabeza et al., 2002; Stern, 2009). However, a more recent investigation has suggested that contra-lateral activation is age invariant and the manifestation of increased subjective task demand rather than ageing. This perspective was put forward in the Compensation- Related Utilisation of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008). As such, the findings of this thesis do not support this hypothesis but rather support the idea that contra-lateral activation is the product of older brains trying to keep up with younger brains rather than younger brains working harder.

One explanation as to why the findings in this thesis do not support the contemporary research may be found in the differences in the methodology used. In the current thesis, a visual field paradigm was used in which stimuli of increasing difficulty were either matched across hemispheres or within hemispheres. In the case of the results of this thesis, younger adults did not show an advantage at higher levels of task demand. Previous studies that have indicated processing in both hemispheres for younger adults in response to a subjectively difficult task demand have done so through imaging methodology. That is, bilateral activation is observed in relation to high levels of task demand, regardless of age (Schneider-Garces et al., 2010).

Given the correlational nature of imaging studies, greater functional significance can be attributed to the visual field paradigm. In matching stimuli across hemispheres and comparing to within-hemisphere matches, this method fixes the stimulus to the dependent measure i.e. the reaction time. There can be no guarantee with an imaging study demonstrating contralateral activation in response to increased task demand that the observed activation is not related to more explicit cognitive processing in terms of strategy change. Whilst this is a method of compensation, it does not fit with the idea of the neural mechanism implied by the CRUNCH hypothesis. In relation to other tasks which have used both the visual field paradigms and task demand as well as including younger adults, the study by Guzzetti & Daini (2014) did not show a significant advantage for across hemisphere presentation of the harder stimuli. Whilst the authors speculate that this may be corrected if task demand was controlled for between older and younger participants, their current finding supports the findings of this thesis.

Given the finding in this thesis that neural compensation across hemispheres is not manifest in younger adults, this mechanism must be the result of neural reorganisation during the latter stages of lifespan (Cabeza et al., 2002). What remains to be seen, however, is how and why such a mechanism might exist under these circumstances. It appears at odds economically for age-related biological decline to trigger the organisation of neural pathways into a processing conduit between two hemispheres. One of the possible answers to this question would be that processing across hemispheres is a result of a fortunate accident which is the result of age-related decline in the corpus callosum interacting with an already present mechanism suggested by the model in Chapter two. Further, the overall decline in dopamine may lead to less specialisation in one of the hemispheres (S.-C. Li &

Lindenberger, 1999) and therefore provide a more economical candidate for recruitment than more specialised modules even though the latter may be geographically closer.

Another possible explanation for how age-related biological decline can lead to a compensatory action, as suggested by the findings of this thesis, comes through the functionality of the corpus callosum (CC). The finding that contra-lateral activation and compensation are the preserve of older adults supports the behavioural and modelling studies which have suggested that decline in the CC leads to the reduction of and inhibitory influence of one hemisphere over the other (Denenberg et al., 1986; Levitan & Reggia, 2000). Such a view may support two different approaches to hemispheric cooperation which change from one to the other over age. Initially, direct access (Bogen, 2000; Iacoboni & Zaidel, 1996) between the hemispheres may be occurring with inhibitory influence suppressing contralateral processing. However, as ageing persists, a decline in inhibitory influence would mean greater cooperation between the hemispheres (Pulvermüller & Mohr, 1996) with some benefit for harder stimuli prior to a collapse in resources. Such a move would not mean a despecialisation of the functionality but rather a cooperative effort to process the information (Weems & Reggia, 2004). In the model by Monaghan & Pollmann (2003), an advantage for bilateral presentation of more complex stimuli is driven by the architecture of the model and therefore the change towards a bilateral advantage for subjectively difficult stimuli in older age must be due to age-related changes in the neural connectivity of the two hemispheres.

Further support for the lack of age-invariance in neural compensation comes from another theory of neural compensation which has been briefly described in this thesis, the Posterior to Anterior Shift in Activation (PASA). In results similar to those suggested by this thesis, even when high subjective difficulty was controlled for, the pattern of posterior and anterior activation was different between older and younger adults (Davis et al., 2008). That is, any age-related reduction in typical activity was related to an age-related increase in prefrontal cortex (PFC) activity. This change in activation pattern for older adults only, independent of task and task difficulty correlated with task performance. PFC activity positively correlated with performance and occipital activity negatively correlated with task performance. These findings and the results of the current thesis support a view of compensation which is specific to older adults and not task difficulty. However, to date, no mechanism to explain this phenomenon has been put forward beyond the idea that one region comes online in support of the other.

6.8 STAC

Given the wide theoretical reach of the Scaffolding Theory of Ageing and Cognition hypothesis (STAC; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014), the implications that the current research has upon this are many. This theory already incorporates neural reserve and neural compensation but also takes in a number of different aspects of the ageing process itself. Compensatory scaffolding is seen as the result of a number of different neurological processes. These include neurogenesis, distributed processing, and frontal recruitment as observed in the PASA model. Furthermore, bilaterality is seen as a contributing factor. The results of this thesis provided greater validity for this perspective in providing a mechanism by which bilateral processing can occur. The neural network model in this thesis provides support for the assertion that training and cognitive activity promote scaffolding. The model demonstrated the link between repeated use of a second language over age and the distribution of the semantic representations.

Further support provided by the research in this thesis to the STAC hypothesis is the suggestion that there is variability with regards to neural compensation in younger adults. This is due to scaffolding being the result of both direct challenge and age-related experience. This is not to say that the authors ignore their own literature with regards to bilateral activation being driven by task demand rather than age (the CRUNCH hypothesis; Reuter-Lorenz & Cappell, 2008). However, the description of neural compensation in the context of the STAC hypothesis is the result of an interaction between events over the lifespan and the challenge faced by increased task demand. Furthermore, those younger adults who do use scaffolding characteristics of older adults are themselves subject to accelerated neurological decline (Park & Reuter-Lorenz, 2009). Therefore, the STAC theory suggests that there is great variability in younger adults with regards to the capacity to engage neural pathways which facilitate neural compensation. In this respect, the results of this study can be seen as compatible with the STAC theory. Neural compensation was not observed as occurring in younger adults in the experiments in this thesis. However, it would stand to reason that those individuals early on in adult life such as university students commonly used as participants, would not demonstrate such a large effect for across-hemisphere presentation at high levels of task demand compared to an older individual who has undertaken years of scaffolding enhancement through life experience, as described by the proxies of cognitive reserve. Theoretically, neural compensation is not just the preserve of older adults. However, it is much more likely to be behaviourally manifest in that group.

6.9 What was surprising?

The behavioural study in chapter two demonstrated that even at levels of task demand which were difficult for healthy young adults, no advantage for presenting the matching stimulus across the hemispheres was found. This was contradictory to the viewpoint given as part of the CRUNCH model (Reuter-Lorenz & Cappell, 2008). One of the immediate suggestions to reconcile this finding was to look at the nature of the data provided. Given that the stimulus used was novel, it may have been that the stimulus was not difficult enough, something which was already reported as impractical to increase. However, upon examining the data in terms of error rates, it was found that the data reflected a steady increase in task difficulty with the exception of a bump at the lower levels. These results were therefore interpreted as being indicative of a population in which the ability to compensate bilaterally was variable, in accordance with the STAC hypothesis (Reuter-Lorenz & Park, 2014).

Given some of the more recent reviews about the lack of a bilingual advantage, it should not be particularly surprisingly that there was a very poor predictive relationship between language scores reflecting a use of multiple languages and performance in executive control studies (de Bruin et al., 2015; Paap & Greenberg, 2013). However, given the support that a bilingual advantage has been provided (Bialystok, 1999; Filippi, Leech, Thomas, Green, & Dick, 2012; Prior & MacWhinney, 2010), some effect was expected.

The significant difference in errors in the Stroop task between those individuals who had stated that they had any experience of a further language and those who had none was a surprising result. This was due to the non-significant result when a more distinct sample bilinguals was derived and compared to the monolinguals. Similarity in effect sizes between these two comparisons suggest that only a small amount of exposure to a second language is sufficient to provide a bilingual advantage and that significance of one and not the other was a case of the small amount of participants in the strong bilingual group. This finding, if real, suggests that limited exposure is enough to produce a ‘bilingual’ advantage in inhibitory tasks. However, given that task switching also has an inhibitory component and no difference was found in this task, the effect may be small and limited to tasks for which inhibition plays a large role. More research is needed to explore the relationship between the levels of second language exposure and the bilingual advantage. Further research may also demonstrate whether there is a ‘sweet spot’ in bilingualism which exists between the benefits of increased cognitive control and the penalties related to recall incurred by an increased clustering of representations.

6.10 Measuring cognitive reserve

Investigation within this thesis has also called into question the suitability of using questionnaires to measure cognitive reserve. A number of longitudinal studies have successfully used environmental proxies in relation to clear associations between schools in these proxies and the ability to offset cognitive decline in older age. However, newer questionnaires have been developed that measure cognitive reserve as a result of multiple proxies to produce a cognitive reserve score. Whilst this appears to be a useful addition to the methodological armoury, further investigation is needed to understand the differing contribution that the different proxies make to the offset of cognitive decline. Furthermore, different questionnaires take into account different factors. To be able to relate measures of cognitive reserve to behavioural or imaging-based measures is to be sure of the content validity of such measures.

Measures based on environmental factors may provide an indication of cognitive reserve. However, the results that have demonstrated a lack of relationship between behavioural measures of cognitive control and proxies of cognitive reserve may suggest that a clearer picture of cognitive reserve in an individual should arise as a result of investigating clear biological correlates. The negative relationship between cognitive reserve measured by proxies and brain activation gives some illustration of the real biological changes underpinning cognitive reserve (Zhu, Hakun, Johnson, & Gold, 2014). However, more explicit biological measures will arrive with improved imaging techniques to provide an increasingly clearer picture of causality.

6.11 The benefits of using models to explore theories of cognitive reserve

Computational models of cognitive reserve can provide an indication as to the causal nature of the mechanisms which contribute to this phenomenon. Such models allow investigation beyond the correlational imaging studies due to the ability to manipulate any facet of the model and investigate the resultant outcomes. For example, in the model in chapter two, age was manipulated by changing the strength of recurrent connections to the representations in the buffer level, allowing all other features of the model to remain constant. In chapter four, age was characterised by declining neural responsiveness represented by changing the gain in the transfer function whilst again keeping all other features of the model constant over multiple simulations.

The models in this thesis employed two biologically plausible instantiations of the ageing process. The use of other computational mechanisms of ageing should be employed in future studies together with further implementations of the models already used. For example, one of the more commonly used mechanisms applied to neural networks would be lesioning. This technique could be applied to both weights and/or nodes. An incremental version of this would be the reduction in weight values over time as a representation of neural degradation. A different perspective on neural noise might include adding values to input vectors as a simulation of environmental noise or adding value to the weights to represent internal noise.

6.12 Limitations and future directions

One of the major limitations of this study is a chronological one and relates to future research. A large amount of studies within this area rely on longitudinal data. Therefore, given the size of both samples in the final behavioural study in this thesis, longitudinal data may provide some indication of the relationship between the ability to offset cognitive decline and proxies of cognitive reserve. These might include the relationship between the scores reported in the CRIQ and performance in executive control tasks. This limitation is linked to the time attributed to complete the thesis. However, future studies may revisit some of those individuals who took part in the CRIQ questionnaire for further testing

Due to the dominance of the English language in both samples undertaking each of the executive control tasks, it was thought that it would be acceptable to include

English colour words in the Stroop task and English prompts for the tasks in the task switching experiment. Given this, there may have been confounding effects of the colour words from the Stroop task being in English and therefore automatically providing some slowdown in terms of lexical access for the small minority of individuals in the sample for Stroop experiment. More of a concern was the use of English as a prompt for the two-dimensional task switching experiment given the large amount of multilinguals who may not have had English as their heritage language. Lexical access may have been delayed to some extent and therefore advantage in executive control in bilinguals may have been offset by this delay. Future research which includes both executive control processes and measures of cognitive reserve may use non-lingual versions of the appropriate cognitive tasks.

To suggest that carrying out a particular task or multiple tasks over the lifespan leads to an increase in grey matter volume has already been posited (e.g. Solé-Padullés et al., 2009). However, it appears counterintuitive to suggest that the neural substrate accrued through lifelong practice of particular tasks or procedures is not in some way related to those processes. At least one imaging study has suggested a biological basis for the link between bilingualism and additional neural substrate (e.g. Gold et al., 2013). However, the results of this thesis demonstrate that those biological differences in bilinguals are not manifest in improvements in executive control. Therefore further research must examine the link between bilingualism and the exact cognitive processes which the biological differences underlie.

In terms of the direct relationship between bilingualism and cognitive reserve, supporting studies in the literature continue to be forthcoming (e.g. Kowoll et al., 2016). However, the null findings with regards to a predictive relationship between bilingualism in younger adults and executive control are indicative of the broken link between the underlying neural substrate and offsetting cognitive decline. Therefore, a final answer as to the question of what cognitive reserve is may include the suggestion that additional brain built up through continual practice of procedures or tasks is flexible enough to provide compensation for any cognitive process. However, in terms of any explicit cognitive advantage, this may be purely incidental.

Given the observed lack of a compensatory mechanism in younger adults given increased task demand, the search for a neural basis to an age-related mechanism appears necessary. The meta-analysis and computational model in chapter two suggest one avenue of enquiry. A relationship between activation in the rostral PFC and the ACC has already been suggested with some early enquiry pointing to a further relationship with task demand. However, future research might attempt to quantify task demand and apply it to the studies in this meta-analysis in an attempt to establish a relationship between all three variables. Such work may also be applied to the PASA model given the lack of age invariance in the activation data. Given the conflict monitoring functionality of the ACC, investigation of activation in this region in relation to the PASA pattern may form an initial line of enquiry.

6.13 Summary

This thesis has taken the two biggest theoretical aspects of cognitive reserve, neural reserve and neural compensation, and carried out a multi-methodological investigation in an attempt to address the question as to what the mechanisms are behind this concept. The research contained within this thesis suggests that when it comes to neural compensation, the neural architecture may already be in place for a system that detects task demand and triggers the recruitment of new resources from elsewhere. However, this system, or factors which contribute to it, is triggered as a result of the ageing process itself.

With regards to the other aspect of cognitive reserve, neural reserve, this thesis focused on one particular aspect as an example of an ecological proxy of this factor, bilingualism. Where cognitive effort might be represented as less activation in brain with higher cognitive reserve, the specific benefits in terms of specific cognitive functionality are not manifest in younger bilinguals, at least in terms of executive control. The same can also be said of other proxies of cognitive reserve, such as lifestyle and education.

From a methodological perspective, the investigation carried out within this thesis has produced two methods of investigating cognitive reserve that may contribute to the gathering of further knowledge in this field. An enhanced paradigm which successfully pushes the level of task difficulty in visual field studies has been created which can serve as a guide for future studies in this area. Furthermore, a way of representing separation of representations has been created which can be implemented during the training of the neural network model to provide a more realistic longitudinal picture of the gradual development of representational space. The application of many approaches to the study of cognitive reserve including computational modelling, large-scale behavioural studies, multilevel modelling, and meta-analysis has provided a thorough examination of the subject as well as a comprehensive experience of research methods for the author.

Overall, cognitive reserve has not revealed itself as an increase in any particular cognitive functionality in younger adults. Its manifestation in older adults as a delayed onset of cognitive decline may be as simple as additional brain areas available from which to draw resources. The complexity in cognitive reserve may be tied up with the mechanisms behind the recruitment of such a resource. As such, the ‘cognitive’ in cognitive reserve contributes to the build-up but its description and the manifestation should remain on the biological level of description.

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Appendix A – Comparing between hemisphere matches

Additional analysis carried out from chapter three data on between hemisphere matches, probe on the left vs probe on the right.

Task difficulty (1 = easy, 5 =difficult)	Contralateral match direction Probe-Target	Mean	SD
1 = Dot matching, two probes	L-R	776	116
	R-L	767	114
2 = Dot matching, four probes	L-R	927	157
	R-L	953	159
3 = Number matching, two probes	L-R	852	112
	R-L	885	119
4 = Number matching, four probes	L-R	954	158
	R-L	980	181
5 = Number matching, parity check	L-R	1088	224
	R-L	1097	209

The results of a two-by-five ANOVA demonstrated no effect for the direction of the match (F (1,88) = 2.434, p=.133). Task demand continued to provide a significant main effect (F (4,88) = 25.016, p<.001) with no interaction between direction of the match and task demand (F (4,88) = 0.929, p=.451).

Appendix B – Chapter five questionnaire

Full questionnaire booklet provided to participants in studies I and II in Chapter five

Section A

Age ____

Type of location lived longest (Please circle)

1 = Remote Countryside   7 = Inner City

1   2   3   4   5   6   7

Education

Years of education (Secondary school education = 12 years) _____

Additional vocational training (put down 0.5 years for every 6 months)   _____

***

Section B - Language

Have you learned any languages aside from your native language? (Please Circle)

Yes/No

(If you answered ‘No’, move directly to section C)

How many _____

At what age did you learn them in years (aside from native language)?

Language 1 ___

Language 2 ___

Language 3 ___

How often do you use your additional languages? (Please circle one option from each modality for each additional language that you have)

Language 1

Conversation (Weighted scores X2)

Daily weekly monthly less than monthly never

Reading

Daily weekly monthly less than monthly

never

Media (Videos, TV)

Daily weekly monthly less than monthly

never

Language 2

Conversation (Weighted scores X2)

Daily weekly monthly less than monthly

never

Reading

Daily weekly monthly less than monthly

never

Media (Videos, TV)

Daily weekly monthly less than monthly

never

Language 3

Conversation (Weighted scores X2)

Daily weekly monthly less than monthly

never

Reading

Daily weekly monthly less than monthly

never

Media (Videos, TV)

Daily weekly monthly less than monthly

never

***

Section C – Working Activity

Indicate working years rounded off on a five-year scale (0-5-10-15-20, etc.; e.g., if you have been working for 17 years, write down 20).

Report on all working activities, even in the case of simultaneously held multiple jobs.

Low skilled manual work (farm work, gardener, housemaid, caregiver, waiter, driver, mechanic, plumber, call centre operator, babysitter, etc.)

_____

Skilled manual work (craftsman, cook, store clerk, tailor, representative, serviceman/servicewoman, hairdresser, clerical worker, nurse, etc.)

_____

Skilled non manual work (business owner, white-collar employee, sales agent, priest or monk/nun, real estate agent, nursery school teacher, musician, etc.)

_____

Professional occupation (Managing director of a small company, lawyer, qualified freelance professional, contractor, doctor, teacher, engineer, etc.) _____

Highly responsible or intellectual occupation (Managing director of a big company, senior manager, judge, academic, surgeon, politician, etc.)

_____

Section D – Leisure Time

Please read the instructions carefully

Each question refers to activities carried out regularly throughout adult life (i.e. from 18 years onwards).

All paid activities are excluded from this section and should be included in section C

Tick the box of the activity according to how often you might carry out an activity and put how many years you did this for in the *years* column, even if you don't do it anymore. Put the years in to the nearest 5 years. For example, if you read a newspaper regularly for 27 years, tick Often/Always and put in 30 years, even if you don't do it anymore.

Activities associated with weekly frequency

Reading newspapers and magazines ☐ Never/Rarely ☐ Often/Always

Years ___

Domestic chores (cooking, washing,

Grocery shopping, ironing, etc.) ☐ Never/Rarely ☐ Often/Always Years ___

Driving (not biking) ☐ Never/Rarely ☐ Often/Always Years ___

Leisure activities (sports, hunting, dancing, chess, coin collecting, etc.) ☐ Never/Rarely ☐ Often/Always Years ___

Using new technologies (digital cameras, computer, Internet etc.) ☐ Never/Rarely ☐ Often/Always Years ___

Activities associated with monthly frequency

Social activities (political parties,

Recreational clubs, associations, etc.)☐ Never/Rarely ☐ Often/Always

Years ___

Cinema, theatre ☐ Never/Rarely ☐ Often/Always

Years ___

Gardening, DIY, small-scale

operations such as knitting, etc. ☐ Never/Rarely ☐

Often/Always Years ___

Looking after grandchildren/nieces/

nephews or elderly parents ☐ Never/Rarely ☐ Often/Always

Years ___

Voluntary work ☐ Never/Rarely ☐

Often/Always Years ___

Artistic activities (music, singing,

performance, painting, writing, etc.) ☐ Never/Rarely ☐ Often/Always

Years ___

Activities associated with annual frequency

Exhibitions, concerts, conferences ☐ Never/Rarely ☐ Often/Always

Years ___

Journeys lasting several days ☐ Never/Rarely ☐ Often/Always

Years ___

Reading books ☐ Never/Rarely ☐ Often/Always

Years ___

Activities with fixed frequency

Children ☐ No ☐ Yes

Number ___

Pet Care ☐ Never/Rarely ☐ Often/Always

Years ___

Managing Bank account ☐ Never/Rarely ☐ Often/Always Years ___

Thank you for taking part

Please see overleaf for a debrief

****

Study Debriefing

This questionnaire is based on previous cognitive reserve questionnaires but also includes a section about language. There is a growing body of evidence that suggests that having more than one language and using it contributes considerably to levels of cognitive reserve, a buffer against neurological insult, normally associated with dementia. Further, the ability to inhibit information, such as the non-relevant language in a given situation may be the key to what it is about a second language and cognitive reserve. Therefore, your performance in the stroop test which you may have taken part in, may also be a good indicator of your level of cognitive reserve, regardless of second language use.

How was this tested?

Your scores on the general cognitive reserve questions (All but the language section) and the language section of the questionnaire will be correlated with your performance in the stroop test. This would be carried out to see if there were any associations between your level of cognitive reserve according to the normally used items and the language and stroop measures.

Hypotheses and main questions:

We would expect that performance that people scoring highly on the language section would also score highly on the stroop test. These scores should also positively correlate with the scores on the other answers to the questionnaire.

Why is this important to study?

A strong correlation between scores on the questionnaire and scores on the Stroop test would indicate that the development of strong central executive processes through occupation, pastime or second language use is the key to cognitive reserve in human beings. If this is the case then this faculty could be developed independently through cognitive training and provide a more direct path to offsetting cognitive decline.

What if I want to know more?

If you are interested in learning more about cognitive reserve, please take a look at:

Stern, Y. (2003). The concept of cognitive reserve: a catalyst for research. *J Clin.Exp.Neuropsychol.*, *25*(5), 589–593.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015–2028.

If you would like to receive a report of this research when it is completed (or a summary of the findings), please contact Nick Rendell at 0207 073 8009, nrende01@mail.bbk.ac.uk.

If you have concerns about your rights as a participant in this experiment, please contact ethics@psychology.bbk.ac.uk.

Thank you again for your participation.